**ELECTRICAL ENGINEERING DEPARTMENT**

**California Polytechnic State University**

**Senior Project Final Report**

# Power Line Coupling Power Supply Design

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# Abstract

In this project, a power supply was designed for a startup company, Perch Sensing, to detect wildfires with the use of distributed sensors across power lines. The purpose of the power supply is to provide 15W of power to a microcontroller, which controls the sensor nodes. The power supply hangs from power lines and draws energy by inductively coupling to these lines. Our design starts with a current transformer that steps down the current from the power line, which is fed into a shunting mechanism as a safety precaution when the load is absent, then to the power supply itself. The power supply design uses a full wave bridge rectifier, SEPIC DC-DC converter, and filters to output the desired power while maintaining a set output voltage with as little ripple as possible. Based on the simulation results, our design had an output voltage peak to peak ripple of 36mV, was able to successfully supply a load of 15W at 5V and had less than 3% load and line regulations. However, the highest overall efficiency did not exceed 66%, and so recommendations are provided to further improve this design.

# Chapter 1: Introduction

Electronic devices have affected nearly every aspect of our lives by redefining the way we connect with one another, perform our daily tasks, and improve our overall quality of life. Every electrical device requires power, and most need it in a different form than their source supplies. To convert electrical power, we use what is known as power electronics. Power electronics focuses on converting power efficiently with minimal distortion. The power electronic circuitry is used in nearly everything, from the chips in computers, to the lights in our houses, to renewable energy. Depending on the needs of the circuit, power electronics can step up voltage, step down voltage, convert from DC to AC or from AC to DC.

We often need AC-DC converters to convert the AC power in our wall outlets to the DC power our smartphones and laptops require. The rectifying circuit that connects the two sides can have two main configurations which are midpoint and bridge rectifier circuits. The midpoint configuration utilizes a transformer which isolates the AC and DC sides and uses half the number of diodes needed for a bridge configuration. The bridge rectifier circuit does not use a transformer. Instead, it needs four diodes for a single-phase AC input, and six diodes for a three-phase AC input. Rectifiers can use diodes or thyristors, or both. When diodes are used, it is called an uncontrolled rectifier, and when thyristors are used instead, it is called a controlled rectifier. Controlled rectifiers provide adjustments in their thyristor’s “firing angle”, where the control circuit can generate a specific triggering pulse. When the rectifier includes a combination of diodes and thyristors, it is a semi-controllable rectifier.

When observing the quality of the DC output of a rectifier, the half wave rectifier converts negative cycles of the AC waveform to be zero, whereas a full wave rectifier converts the negative cycles to a positive waveform. Smoothing capacitors and filters can be appended to rectifying circuits to improve the DC output. Rectifier circuits are essential to power electronics by providing one of the first main steps in a power supply or electrical system.

Another type of power circuit is the DC-DC converter. DC-DC converters provide an efficient form of power transfer between circuits of different DC voltage levels. This conversion is especially important in power electronics as different loads have different voltage and current source specifications. The use of DC-DC converters simplifies power supply design such that the same power source can be used for multiple circuits. Similarly, voltage dividers and linear regulators are commonly used to transform a source to different voltage levels, however, these circuits are not nearly as efficient as DC-DC converters. There are two types of DC-DC converter topologies: non-isolated and isolated. Non-isolated DC-DC converters have one continuous circuit in which current flows uninterrupted from the source to the load. Common topologies for non-isolated DC-DC converters are the buck, boost, and buck-boost. Buck converters are used to step-down voltage while boost converters do the opposite: step-up voltage. Buck-boost converters can both step up and step-down voltages.

Isolated DC-DC converters use a transformer to electrically separate the input from the output. Push-pull, forward, and flyback converters are all common topologies with the same functions as their non-isolated counterparts. An isolated design offers more protection by separating the source side from the load, protecting the load from any spikes in source voltage or current. However, this comes at an increased cost of production and space in comparison to non-isolated topologies. Generally, DC-DC converters are robust circuits that are capable of withstanding large voltage and current fluctuations on the input. In addition, DC-DC converters can safely, efficiently, and reliably output power which make them popular circuits to include in power supply design especially for small-scale electronics.

Combining AC rectifiers and DC-DC converters allows us to use the standard AC system to power any DC circuit.  On a larger scale, power electronics help to save money and reduce energy consumption. A compact but efficient power supply design provides the foundation for building reliable, and efficient systems.

# Chapter 2: Background

In 2019 alone, wildfires devastated over 4.7 million acres of land across the country [1]. Wildfires wreak havoc in California, Oregon, and Washington with over 5 million acres burned to date [2]. According to [3], natural disasters annually displace over 25.3 million people from their homes. These tragedies have made early fire detection more important than ever. Preventable wildfires take from communities in the form of health care costs and, in some cases, lives. Adapting to these increasingly drastic events means detecting and preventing natural disasters from the environments in which they begin.

A startup company called Perch Sensing aims to do just this by creating an environmental sensing platform, which monitors environmental conditions in remote, high-risk areas using sensors and cameras [4]. Utility companies distribute this device throughout the power grid to monitor the surrounding environment and investigate abnormal activities. Our project aims to power the environmental detection system using the utility lines themselves. Various methods have proven to be successful in harvesting energy from power lines. These techniques include harvesting energy from magnetic fields and electric fields as well as piezoelectricity [5]. Through our research, we have found harvesting energy from magnetic fields to be the most promising method. Harvesting energy from magnetic fields in power lines has been used before, such as those explored by Wu and Najafi [6,7].

In [6], the authors focus on the energy harvesting design of their system from a utility line by using a rectangular coil with a laminated electrical sheet core, which was modeled after a transformer. The goal of this design was to provide a low-cost option to harvest larger amounts of power by varying the load resistor. However, for our project, a commercially available transformer would be more reliable in supplying power and more realistic given the timeline for our project. The energy harvester in [6] was able to successfully power a gas sensor board with the use of a power management circuit, so this design helped guide our decisions for our project.

Similarly, in [7], the authors designed an energy harvester with a split-core design. The main goal of this project was to design an energy harvesting system for an overhead transmission line condition monitoring network. In addition to the energy harvester, the authors designed a power processing unit which consists of a power electronic circuit to rectify and convert the output of the energy harvester. This design was able to harvest as much as 55W from the power line. Overall, [6] and [7]'s designs are variations of our project. They prove that harvested energy from utility lines can safely power sensor-based systems.

The project described in [8] provides a great example of environmental detection using sensors and a transformer on a power line. This project also powers a microcontroller-based sensor system using a current transformer and power electronics. Unlike our project, the previous design was meant to collect various data on environmental and fault current information through distribution lines. Our project focuses on alerting utility companies of any environmental anomalies. While our product focuses on alerting companies of environmental anomalies rather than continuously reporting environmental data, the power electronics required are very similar. One area of improvement that was noted in the previous design is outputting a constant 5V supply for the system and limiting current shunting to ground. A different controller topology allows the design to provide more power to the system and more efficiently than the previous design.

Based on our research, our power supply design goal is to combine 3 different circuit stages: an inductive coupling stage, a rectifying stage, and a DC-DC converting stage, to successfully power a microcontroller-based sensor system. The inductive coupler harvests magnetic fields coming from the line and the rectifying stage turns this AC voltage to the DC voltage, more suited to microcontrollers and sensors, as exemplified in [9]. The third stage steps up or steps down the DC signal to the proper voltage level for the microcontroller. The main objective of this project is to combine multiple stages to create a functional power supply that provides sufficient power to sensors. This project chiefly aims to reliably power sensors because the Perch Sensing system is designed to reliably detect and prevent wildfire damage in order to save lives.

# Chapter 3: Design Requirements

This power supply design project aims to output DC power to a microcontroller, which powers the sub-circuits and sensors for Perch Sensing's environmental detection device. As noted on the microcontroller datasheet, a constant 2.5A and 5V is needed for operation. The allowable output current and voltage ripple is 0.5A and 0.5V, respectively. According to power ratings of the microcontroller, the maximum power output of the power supply is 16.5W. The current transformer in the system also must handle magnetic fields coming from the power lines, produced by primary-side line currents that range between 800A - 1200A.

Each sensor system attaches to power lines in various locations, so the design of the power supply heavily focuses on safety and weight. Since the device exists in various outdoor locations, the product must weigh as little as possible for easy and efficient installation. The device must weigh less than 7 pounds and fit within a 15 cm x 15 cm x 15 cm cube. Since the device detects instances of natural disasters, it must withstand both normal and extreme weather conditions, which for this project, only concerns the operating temperature. Perch Sensing's mechanical team is designing the enclosure which accounts for most of the varying weather conditions, the mechanical attachment to the power line, as well as EMI shielding for the microcontroller. Therefore, this power supply must primarily withstand differing temperatures between 0-75 degrees Celsius. The budget for this project is set by the EE department's senior project fund and any excess costs will be covered by Perch Sensing. Table 3-1 summarizes the Perch power supply requirements and specifications for this project.

*TABLE 3-1: PERCH POWER SUPPLY REQUIREMENTS AND SPECIFICATIONS*

| Marketing Requirements | Engineering Specifications | Justification |
|---|---|---|
| 4 | Output Current: 2-3A | As referenced in [9], the power supply providing the specified current allows the microcontroller to function. Nominal 2.5A specified by Perch Sensing. |
| 4 | Output Voltage: 4.5 - 6.0V | 5V output voltage specified by Perch Sensing. This allows the microcontroller to provide sufficient voltage to the sensors and is within range in [9]. |
| 1, 4, 9 | Peak Power: 9 – 16.5W | Peak power specified by Perch Sensing and [9]. This range ensures sufficient power to the microcontroller and sensors but must not overload them with power and cause them to overheat. |
| 1,9 | Weight < 7lbs | The power supply is transportable and stored on power lines without weighing down the line significantly. Perch Sensing specified this. |
| 2 | Operating Temperature: 0 - 75 degrees Celsius | The power supply withstands extreme temperatures expected in California. High range specified by Perch Sensing; low range specified by climate data [12]. |
| 1, 3,9 | The power supply must fit within a 15 cm x 15 cm x 15 cm cube. | The power supply fits in the enclosure designed for the entire device while allowing sufficient room for the microcontroller and sensors. Dimensions specified by Perch Sensing. |
| 7 | Primary-current range 800A-1200A | The specified range allows the device to handle the currents we expect from power lines in general, which enables sufficient operation of the inductive coupling device. |
| 4, 6 | Ripple peak-peak Voltage < 500mV | This range specifies the maximum ripple for the microcontroller as stated in [9]. |
| 5 | Materials Cost < $600 | Cost estimate based on the budget for the entire device. |
| 8 | Outputs Power via Micro USB | This is the primary way a Raspberry Pi can take in power [9]. |

**Marketing Requirements**

1. Easily installable
2. Weather-resistant
3. Compact
4. Sufficient power output
5. Low cost
6. Low noise
7. Usable on various high-voltage transmission lines
8. Sufficient input and output interfaces
9. Safe

Figure 3-1 shows the power supply design level 0 block diagram input and output. By attaching to the power line, the power supply is inductively coupled to the line to harvest power. The power line current and voltage ratings differ based on location. Therefore, the power supply must account for the common range of 800A - 1200A current that flows through power lines. The power supply has a single output of 5V, 2.5A, which powers the microcontroller.

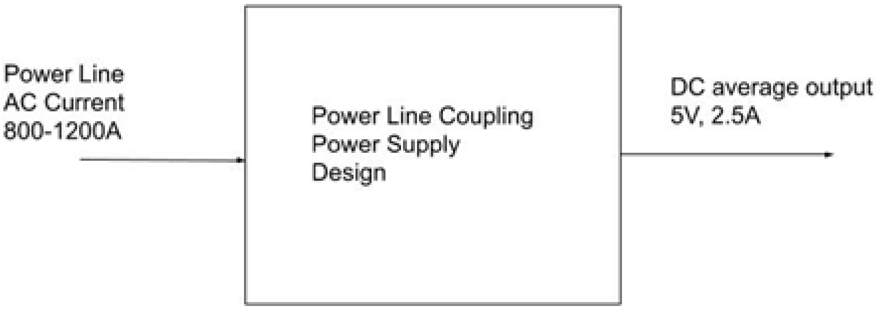

*FIGURE 3-1: PERCH POWER SUPPLY LEVEL 0 BLOCK DIAGRAM*

Figure 3-2 describes the key stages within the power supply. The inductive coupling device harvests the power line current and steps the AC current down. This output peak current is converted to voltage which then being used to supply the next stage, the full-wave bridge rectifier. The rectifier transforms the AC voltage waveform to a “DC” signal, and the switching DC-DC converter steps the voltage up or down, while maintaining a constant voltage for the microcontroller.

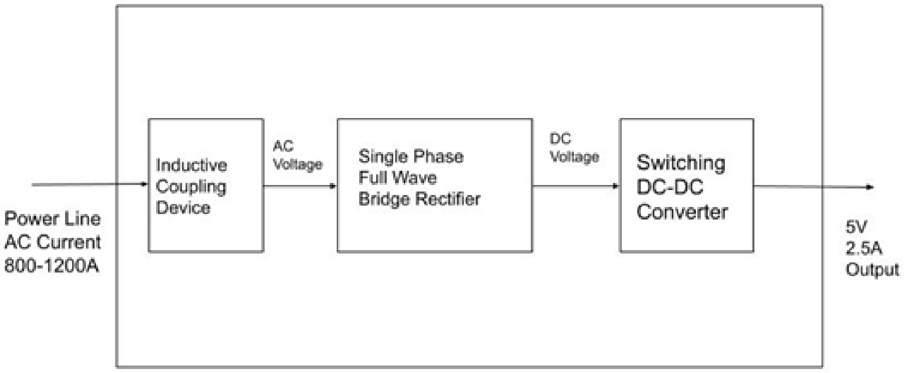

*FIGURE 3-2: PERCH POWER SUPPLY LEVEL 1 BLOCK DIAGRAM*

Figure 3-3 shows the level 2 block diagram, which is a more detailed depiction of our design. The input AC current is stepped down by a 1200:5 ratio transformer. After the current transformer is an optocoupler circuit that limits the amount of current into the bridge rectifier. This AC current is then converted to DC current by the bridge rectifier and filter. This is then stepped up or down in voltage depending on the input voltage relative to 5V. The controller is placed in a feedback loop from the output to the input of the DC-DC converter to better regulate the output of 5V. Finally, the waveform is once again filtered and delivered to the Raspberry Pi. If the microcontroller does not require as much current as is being delivered, excess current is siphoned off to ground by the optocoupler to ensure the circuit is not damaged.

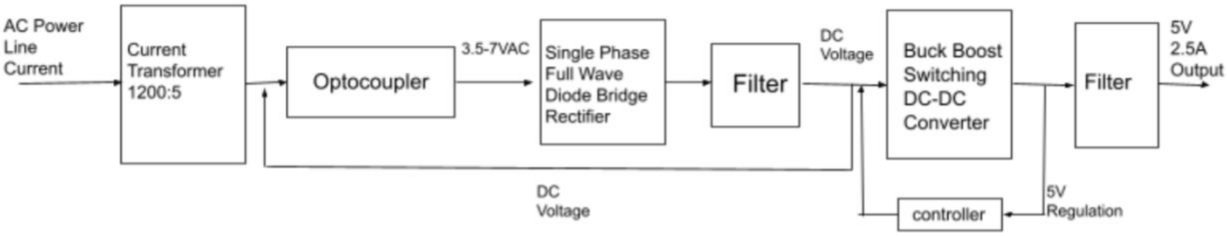

*FIGURE 3-3: PERCH POWER SUPPLY LEVEL 2 BLOCK DIAGRAM*

# Chapter 4: Design

A current transformer is used to inductively couple to the power line and harvest the magnetic energy emitted by the power lines. For ease of installation on the power line, the Square-D Powerlogic 3090 was chosen for it is a split core current transformer. The transformer features a 1200:5 turns ratio which was selected since this device must be versatile and usable on various levels of power lines. This current transformer also has a burden rating of 22.5 VA which represents the maximum load that the secondary side of the current transformer can handle. A larger burden rating was chosen to ensure that the transformer can supply the load as well as the power electronics.

Once the current transformer was chosen, the next step was to determine the current and voltage range on the secondary side under normal operation. As stated previously, current in the power line is expected to fluctuate between 800-1200 A under normal conditions. Given that the DC-DC converter must be able to supply 15 W at 5 V to the load under these conditions, the input specifications to the DC-DC converter was solved for at the best case of 90% and worst case of 70% for DC-DC converter efficiency.

$$Primary\ Current: 1200\ A \quad Secondary\ Current: 5A \quad \eta_{DC-DC} = 0.90$$

$$P_{IN} = \frac{P_{OUT}}{\eta_{DC-DC}} = \frac{15\ W}{0.9} = 16.67\ W$$

$$V_{IN} = \frac{P_{IN}}{I_{secondary}} = \frac{16.67\ W}{5\ A} = 3.33V$$

$$Primary\ Current: 800\ A \quad Secondary\ Current: 3.33A \quad \eta_{DC-DC} = 0.70$$

$$P_{IN} = \frac{P_{OUT}}{\eta_{DC-DC}} = \frac{15\ W}{0.7} = 21.43\ W$$

$$V_{IN} = \frac{P_{IN}}{I_{secondary}} = \frac{21.43\ W}{3.33\ A} = 6.43V$$

With these calculations, the normal conditions for the secondary side were determined to be 3-5 $A_{rms}$ and 3-7 $V_{rms}$. Since the secondary side of the current transformer effectively acts like a current source, current is constantly supplied to the circuit so an optocoupler is used to control the voltage input to the DC-DC converter after rectification and filtering. This is to prevent an overcurrent condition and instability in the circuit. Once the voltage at the input of the DC-DC converter reaches 20V, the optocoupler shorts the two nodes of the secondary side of the current transformer to protect the circuit and reduce power loss. The ratings for this optocoupler are specifically chosen for a threshold voltage of 25V at a load current of 5 $A_{rms}$.

A diode bridge rectifier is used to convert an AC signal to DC and for this component we found the TS10KL60, a bridge rectifier chip, with all four diodes. This reduces space taken up by the components and increases the physical robustness of the diode bridge. There is no LTSpice model for the TS10KL60 diodes so for the purposes of this project a similar diode model will be used from the LTSpice library, the RF2001T2D. The diodes are rated for 10A which is well over the expected maximum current of 5 $A_{rms}$.

The value of the capacitance, C4 was found using the inequality below

$$R_{Load} * C >> \frac{1}{f}$$

where $R_{Load}$ is 1.666 ohms: the theoretical minimum resistance of the microcontroller we power.

This yields a capacitance value of

$$C = 0.01\,F = 10mF$$

For the purpose of this design, however, we used 4mF as this was the minimum simulated capacitance that allowed the system to function.

The possible range of input voltages resulting from the power line fluctuations was calculated using excel, and fluctuates above and below the output of 5 V. Therefore, for the DC-DC converter, a buck-boost or flyback converter is necessary. A flyback design was preferred because it provides isolation between the input and output and uses less components than the buck-boost converter. The LTC1871 Flyback and SEPIC controller was chosen for its wide input voltage range of 2.5 to 36 V and output overvoltage protection. The SEPIC, or single ended primary inductance converter, was chosen because it provides a reduced input ripple current, less stress on the MOSFETs and short-circuit protection on the output. Figure 4-1from the datasheet illustrates the basic SEPIC topology.

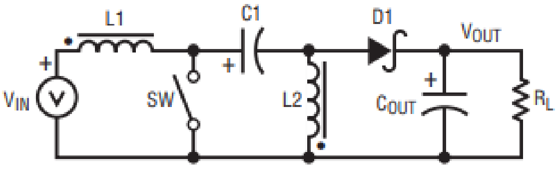

*FIGURE 4-1: SEPIC TOPOLOGY*

In order to provide the 3.3 V necessary to power the DC-DC converter, specifically to pins Vin and SET on the LTC1871, an LDO was used to provide a constant voltage. An LT3082 was used for a few reasons. Firstly, it provides the 3.3 V output necessary. Secondly, it has a wide input range it can handle, from 1.2-40V. As a result, it can handle the fluctuating voltage going into the DC-DC converter. Finally, it has a low current minimum (as can be seen in Figure 4-2), which is perfect for the low current draw of the DC-DC converter.

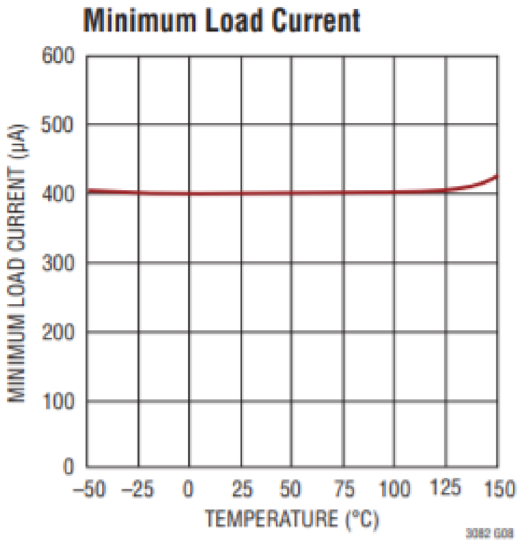

*FIGURE 4-2: MINIMUM LOAD CURRENT OF LT1781*

The output capacitor, C10 was chosen to be 2.2 $\mu F$ as this is the minimum capacitance specified by the datasheet. $R_{set}$ (R6) was chosen to be 332k to set the output voltage as 3.3 V and $C_{set}$ (C9) was set to .1 µF as specified by the datasheet. C1, C2 and R4 are used to properly bias the pin $I_{TH}$, which affects the error in the controller's output voltage. The values for these components come from a reference design from the manufacturer.

Whereas a flyback converter uses a transformer, the SEPIC converter uses two identical inductors, L1 and L2, coupled by a capacitor, C5. When L1=L2, they can both be wound on the same core which reduces the input ripple and the size of the inductors. The LTC1871 datasheet recommended using inductor values in the range of 10uH to 100uH, where lower values can reduce physical size and improve the transient response. Therefore, after multiple simulation iterations, L1=L2=17µH in combination with a 10µF coupling capacitor resulted in the most stable steady state output voltage. To reduce the size of the inductors, the operating frequency is 300Hz, which is set by R1 = 82KΩ, from the following graph.

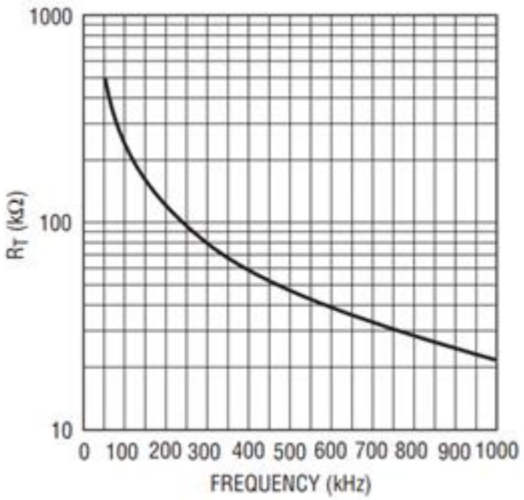

*FIGURE 4-3: TIMING RESISTOR ($R_T$) VALUES*

The output voltage for the controller is set by the following resistor divider formula, where the feedback pin is on the output. Referring to the LT1871 datasheet, R2 is the top resistor and R1 is the bottom resistor of the divider network.

$$V_O = 1.23V * (1 + \frac{R2}{R1})$$

$$5 = 1.23 * (1 + \frac{100k\Omega}{32k\Omega})$$

To maintain fixed frequency operation and operate in discontinuous conduction mode, the MODE pin is connected to the INTVCC pin. A minimum of 4.7µF bypass tantalum or ceramic capacitor, C3, to ground is necessary for the INTVCC pin to supply high transient currents to the gate driver and logic circuitry within the controller. $\chi$ is the percent peak to peak ripple current of the maximum inductor current.

$$D = \frac{V_0 + V_D}{V_{IN} + V_0 + V_D} = \frac{5 + 0.55}{(3.5\ to\ 14) + 5 + 0.55} = 28\%\ to\ 61\%$$

$$I_{L1,pk} = (1 + \frac{\chi}{2}) * I_{O,MAX} * \frac{V_O + V_D}{V_{IN,MIN}} = (1 + \frac{0.2}{2}) * 2.5 * \frac{5 + 0.55}{3.5} = 4.36A$$

$$\Delta I_L = \chi * I_{O,MAX} * \frac{D_{MAX}}{1 - D_{MAX}} = 0.2 * 2.5 * \frac{0.61}{0.39} = 0.782A$$

$$L_1 = L_2 = \frac{V_{IN,MIN}}{2 * \Delta I_L * f} * D_{MAX} = \frac{3.5}{2 * 0.782 * 300{,}000} * 0.61 = 4.55\mu H$$

Increasing the inductor values to 17µH improved the steady state output voltage because of the transient response as mentioned earlier. The Siliconix Si4838DY MOSFET was chosen based on the following $R_{S,ON}$ formula from the datasheet and $V_{DS}$.

$$R_{S,ON} \leq \frac{V_{SENSE,MAX}}{I_{O,MAX}} * \frac{1}{(1 + \frac{\chi}{2}) * \rho_T} * \frac{1}{\frac{V_0 + V_D}{V_{IN,MIN}} + 1} = 11.25m\,\Omega$$

This MOSFET also has a low threshold voltage, allowing the MOSFET to function properly with low voltages seen by the DC-DC converter’s Vin.

The minimum reverse voltage for the diode D1 is shown in the following equation from the datasheet. The Rohm RBR30NS30A Schottky diode was chosen for the 30V reverse voltage and high reverse current capabilities.

$$V_{IN} + V_{OUT} = 14 + 5 = 19V$$

The output capacitors are recommended to consist of a high valued bulk capacitor in parallel with a lower valued, low ESR capacitor.

$$C_{OUT} \geq \frac{I_{OUT,MAX}}{0.01 * V_{OUT} * f} = \frac{2.5}{0.01 * 5 * 300000} = 166\mu F$$

$$ESR_{COUT} \leq \frac{0.01 * V_O}{I_{D,PEAK}} = 11m\Omega$$

The input capacitor for the SEPIC converter depends on the input ripple current from the bridge rectifier so one larger value and one smaller value capacitors were used. The load resistor $R_L$ was chosen to be $\frac{5}{3}\Omega$ to simulate the specific current and voltage through the load at maximum current draw.

Table 4-1 lists the components used for the design. Figure 4-4 shows the final schematic of the proposed power supply and Figure 4-5 is the final KiCad printed circuit board (PCB) layout.

*TABLE 4-1: BILL OF MATERIALS, NOT INCLUDING PCB*

| Count | RefDes | Value | Description | Size | Part Number | Manufacturer | Cost Per Unit | Cost |
|---|---|---|---|---|---|---|---|---|
| 1 | R1 | 82 KΩ | Thick Film Resistors - SMD CRGP 2512 82K 1% SMD Resistor | 0.55mm x 6.5 mm x 3.2 mm | CRGP2512F82K | TE Connectivity | $0.46 | $0.46 |
| 1 | R2 | 32 KΩ | Thin Film Resistors 32K ohm 0.1% 50 ppm High-Precision | 0.45 mm x 1.6 mm x 0.8 mm | RT0603BRE0732KL | Yageo | $0.50 | $0.50 |
| 1 | R3 | 100 KΩ | Thin Film Resistors 0.1% 1210 .25W AEC-Q200 | 0.6mm x 3.2mm x 2.5mm | RN73R2ETTD1003B25 | KOA Speer | $0.98 | $0.98 |
| 1 | R4 | 33 KΩ | Thick Film Resistors 0.4watt 33Kohms 1% 100ppm | .45 mm x 2 mm x 1.25 mm | RCS080533K0FKEA | Vishay | $0.25 | $0.25 |
| 1 | R6 | 332 KΩ | Thick Film Resistors 332K ohm 1% 0.25W | 0.6 mm x 3.2 mm x 1.6 mm | HV732BTTD3323F | KOA Speer | $0.48 | $0.48 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | R7 | 20 Ω | Thin Film Resistors 0.1% 1210 .25W AEC-Q200 | 0.6 mm x 3.2 mm x 1.5 mm | RN73R2ETTD20R0B25 | KOA Speer | $0.98 | $0.98 |
| 1 | R8 | 5 Ω | Thick Film Resistors 20W 5ohm 1% | 4.5 mm x 10.1 mm | D2TO020C5R000FTE3 | Vishay | $12.72 | $12.72 |
| 1 | C1 | 6.8nF | Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 6800pF 0603 10% 10V MLCC | 0.8 mm x 1.6 mm x 0.8 mm | 885012206013 | Wurth Electronik | $0.10 | $0.10 |
| 1 | C2 | 47pF | Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 47pF 0603 5% 10V MLCC | 0.8 mm x 1.6 mm x 0.8 mm | 885012006006 | Wurth Electronik | $0.10 | $0.10 |
| 1 | C3 | 4.7uF | CAP CER 4.7UF 4V X5R 0201 | 0.8 mm x 1.6 mm x 0.8 mm | GRM035R60G475ME15 | Murata | $0.44 | $0.44 |
| 1 | C4 | 3.9mF | Aluminum Electrolytic Capacitors - Radial Leaded WCAP-ATG8 3900uF 25V 20% Radial | 31.5 mm | 860010480024 | Wurth Electronik | $1.98 | $1.98 |
| 1 | C5 | 10uF | CAP CER 10UF 25V X5R 0603 | 0.8 mm x 1.6 mm x 0.8 mm | GRM188R61E106KA73 | Murata | $0.34 | $0.34 |
| 1 | C6 | 330uF | Aluminum Organic Polymer Capacitors WCAP-PSLP 6.3V 330uF 20% ESR=20mOhms | 6.6 mm x 6.6 mm x 5.8 mm | 875105144010 | Wurth Electronik | $0.56 | $0.56 |
| 1 | C7 | 100u | ±20% 6.3V Ceramic Capacitor X5R 0402 (1005 Metric) | 1 mm x 0.5 mm x 0.5 mm | GRM155R60J106ME15 | Murata | $0.19 | $0.19 |
| 1 | C8 | 100uF | Aluminum Organic Polymer Capacitors 25V 100uF 20% ESR=14mOhms | 6.7mm x 5.7mm | A768EB107M1ELAE036 | Kemet | $0.47 | $0.47 |
| 1 | C9 | 100nF | Multilayer Ceramic Capacitors MLCC - SMD/SMT .1UF 6.3V 10% 01005 | 0.4mm x 0.2mm x 0.2mm | GRM022R60J104KE15 | Murata | $0.13 | $0.13 |
| 1 | C10 | 2.2uF | Multilayer Ceramic Capacitors MLCC - SMD/SMT 0603 2.2uF 6.3volts X7R 20% | 1.6mm x 0.8mm x 0.8mm | GCM188R70J225ME22 | Murata | $0.30 | $0.30 |
| 1 | D1 | - | Schottky Diodes & Rectifiers | 330mm x 24mm | RBR30NS30A | Rohm | $1.48 | $1.48 |
| 1 | D2, D3, D4, D5 | | Bridge Rectifiers 10A 600V Standard Bridge Rectifier | 25.3 mm x 13.4 | TS10KL60HD3G | Taiwan Semiconductor | $0.61 | $0.61 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  |  | mm x 10.6 mm |  |  |  |  |
| 1 | Q1 |  | MOSFET 12V 25A 3.5W 3.0mohm @ 4.5V | 4.9mm x 6mm | Si4838DY | Vishay/Siliconix | $1.49 | $1.49 |
| 1 | U1 | - | Switching Controllers No Rsense DC/DC Controller Boost, Flyback & SEPIC | 4.9mm x 3.0mm | LTC1871 | Analog Devices | $6.36 | $6.36 |
| 1 | U2 | - | LDO Voltage Regulators 200mA Programmable 2-Terminal Current Source or Linear Regulator | 0.27mm x 0.53mm | LT3082 | Analog Devices | $4.02 | $4.02 |
| 1 | U3 | - | Triacs 400V .8A Sensing 10-10-10-20mA | 10mm x 29mm | L4X8E8 | Littelfuse | $0.40 | $0.40 |
| 1 | U4 | - | Triac & SCR Output Optocouplers 6Pin800V Optocoupler Zero Cross Triac Dr | 3.53mm x 8.89mm x 6.6mm | MOC3081SVM | ON Semiconductor /Fairchild | $1.34 | $1.34 |
| **Total Cost** |  |  |  |  |  |  |  | **$36.68** |

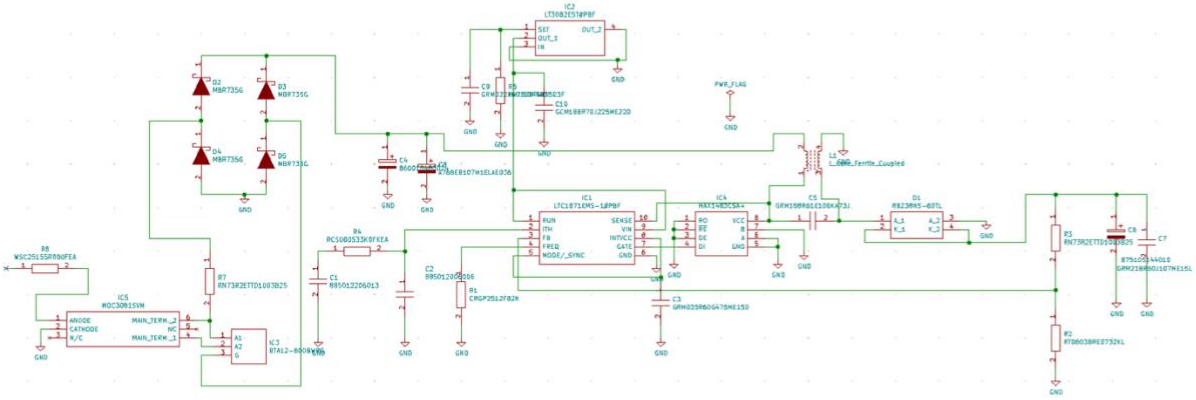

*FIGURE 4-4: KICAD SCHEMATIC*

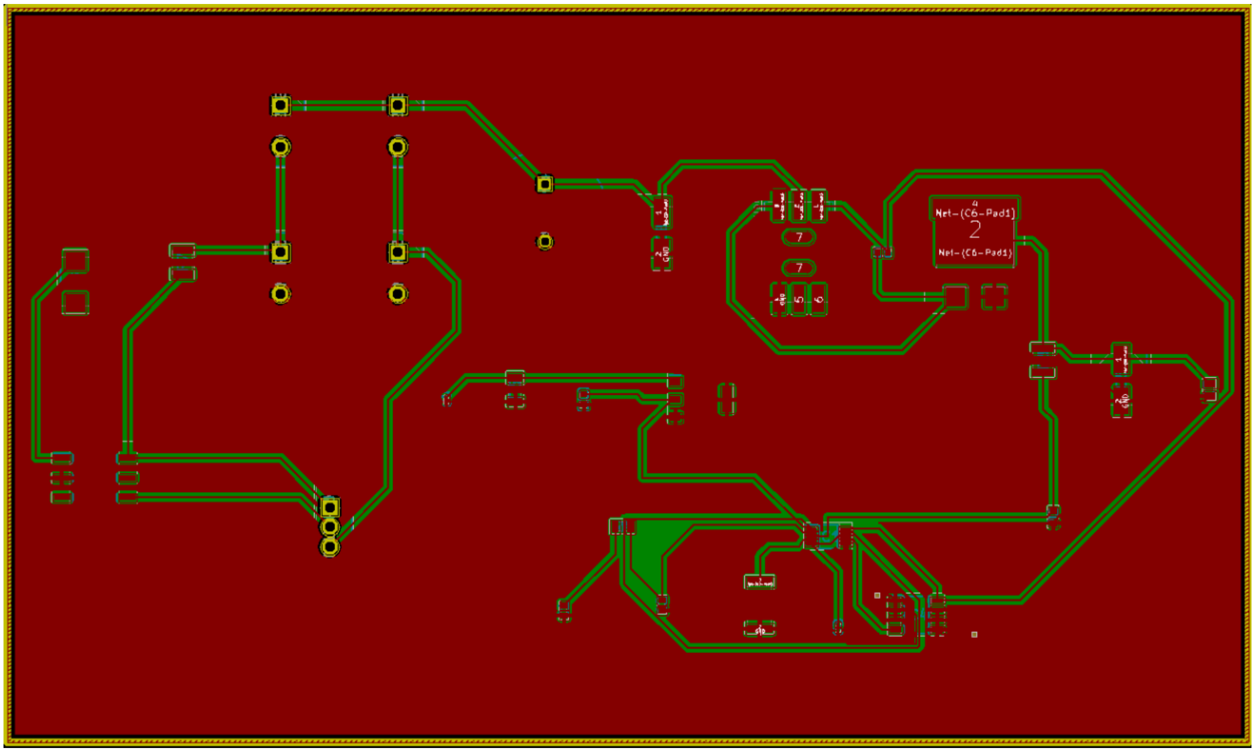

*FIGURE 4-5: KICAD PCB LAYOUT*

# Chapter 5: Simulation Results and Analysis

We chose LTSPICE to simulate our design and to demonstrate its functionality. There are multiple reasons for choosing LTSpice. Firstly, the software provides an extensive array of models for Analog Device's products. Both our DC-DC controller and LDO are made by Analog Devices, so the software streamlined simulation and allowed us to confirm that those specific parts worked. LTSPICE is also free and well documented, reducing design cost and design time respectively. Finally, LTSPICE is commonly used by electrical engineering students at Cal Poly, meaning that future generations can easily understand and further improve our designs.

Figure 5-1 depicts the LTSpice schematic of the design. The first set of simulation testing aimed to ensure the DC-DC controller could output a constant 5V with less than a 0.5V ripple. Using a voltage source at the input from 3V to 7V, component values were adjusted to maintain a constant 5 V output and verify that the DC-DC converter had an output of 15W. The load resistor on the output was set to 5/3 Ω to ensure output power of 15W. After verifying the DC-DC converter was operable at the inputs we found from power line fluctuation calculations in Chapter 4, ideal components were switched to non-ideal before connecting the input of the DC-DC converter to the output of the bridge rectifier. Voltage and current ratings of each component were taken into consideration before choosing a non-ideal component.

After connecting the bridge rectifier to the DC-DC converter we realized we needed a higher voltage at the DC-DC converter input than expected. The DC-DC converter was further altered to adjust for this. The final output of the power supply design was measured to be within the specified peak to peak ripple constraint as shown in Figure 5-2. The lowest output voltage at steady state is 5.045V, and the highest is 5.081V, making the total output ripple 36mV.

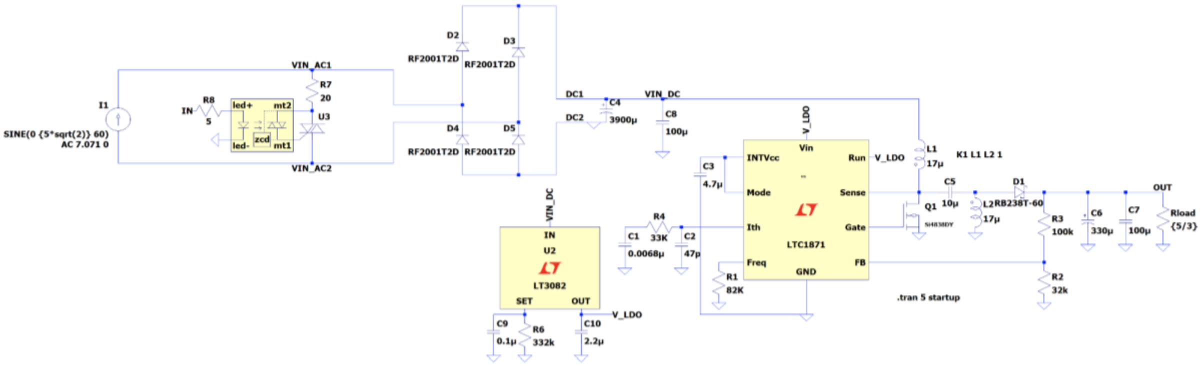

*FIGURE 5-1: SIMULATION SET UP*

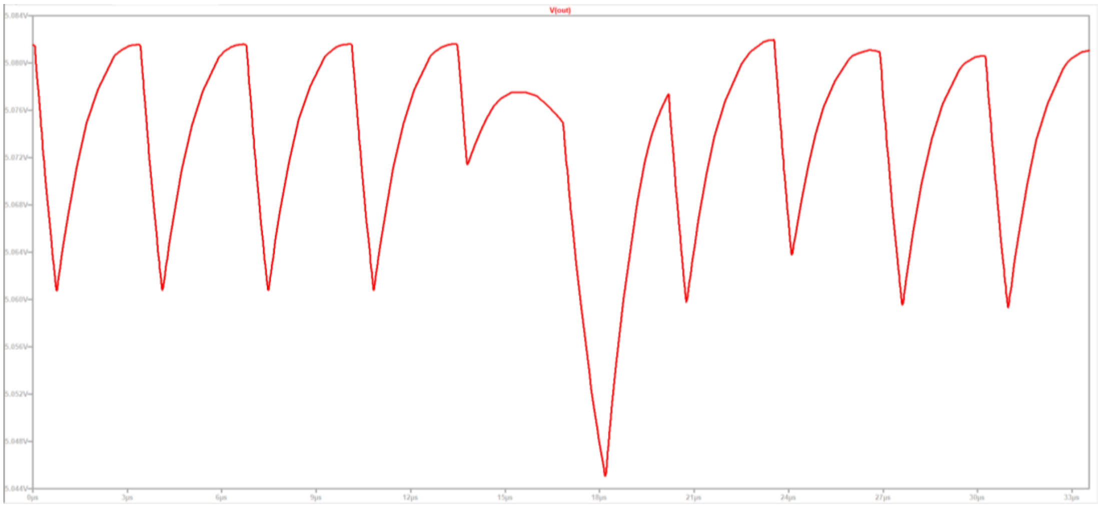

*FIGURE 5-2: STEADY STATE OUTPUT VOLTAGE AT 5 $A_{RMS}$ NOMINAL INPUT CURRENT*

Power measurements were taken at different stages to find the efficiency of each stage and total efficiency of the circuit. We could not use the LTSpice efficiency calculation tool because our circuit features a current source input rather than a voltage source input. The current source was used to simulate the secondary side of the current transformer that outputs between 3-5 $A_{rms}$.

The first power measurement was taken at the common node of the input to the bridge rectifier and the optocoupler. This is because after the current source, the optocoupler is used to shunt current to ground when the input voltage of the DC-DC converter reaches a 26.036V threshold. Ideally, the power loss across the relay would be 0 as $P = I^2 * R$. However, the relay will have a small $R_{dson,}$ and all of the input current is flowing through the relay and this current can be as high as 7.707 Amps peak to peak. The current going through to the input of the bridge rectifier is calculated as the difference between the current source and the current through the optocoupler. The power input to the bridge rectifier is then calculated as the differential voltage of VIN_AC1 and VIN_AC2 multiplied by the current going into the rectifier. The total power dissipated at this node at 5 $A_{rms}$ is 99.708W.

The next power measurement is taken at the output of the bridge rectifier or the input to the DC-DC converter. The voltage at this node is based on the threshold voltage of the optocoupler and is measured at an average voltage of 27.102V. The current measurement is the input current through the inductor, L1 of the DC-DC converter and is an average current of 0.827A. With these two values, the input power to the DC-DC converter is 21.15W.

Since the DC-DC converter is expected to output a constant 15W and the input to the DC-DC converter is 21.15W, the efficiency of the DC-DC converter is calculated to be 73.03%. Using the calculated input and output power of the bridge rectifier, the efficiency of this stage is 21.21%. This lower efficiency is a result from a lot of power being dissipated by the optocoupler and triac, which act as the shunting mechanism for the current source. With these two efficiency values, the total efficiency of the circuit is then 15.49%. The same process is used to calculate efficiency when the current source is supplying 3 $A_{rms}$.

$$\eta_1 = .8577$$

$$\eta_2 = .1849$$

$$\eta_1 * \eta_2 = .8577 * .1849 = .1541 * 100 = 15.49\%$$

*TABLE 5-1: POWER SUPPLY EFFICIENCY*

| Input Current (Arms) | Δ VIN_AC (Vrms) | Rectifier Current (Arms) | AC Input Power (W) | VIN_DC (V) | Inductor Current (A) | DC Input Power (W) | Po (W) | DC-DC Converter Efficiency | Bridge Rectifier Efficiency | Total Efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 27.102 | 3.679 | 99.708 | 25.583 | 0.827 | 21.151 | 15.446 | 73.03% | 21.21% | 15.49% |
| 3 | 9.030 | 2.579 | 23.287 | 13.750 | 1.408 | 19.359 | 15.444 | 79.78% | 83.13% | 66.32% |

The calculated efficiency at 5 $A_{rms}$ and 3 $A_{rms}$ are shown in Table 5-1. At 3 $A_{rms}$, the circuit boasts an efficiency of 66.32% which is considerably higher than the calculated efficiency at 5 $A_{rms}$ which is 15.49%. These results make sense because due to a higher supply current from the secondary side of the current transformer, there is more current being shunted through the optocoupler. This means that there is more power being shunted than being supplied to the load since the load only requires about 15W.

Next is load regulation measurement. Load regulation is the ability of the converter to maintain the set output as the output power fluctuates. To calculate the load regulation of the circuit, voltage measurements were taken at full load and no-load conditions. The following equation was used to calculate load regulation.

$$Load\ Regulation\ = \frac{V_o(no\ load)\ -\ V_o(full\ load)}{V_o(full\ load)} *\ 100$$

In this case, full load condition for the circuit is at 15W or 1.667Ω which is the peak power specification for this project. No load conditions were achieved by removing $R_{load}$ shown in the schematic of Figure 5-1.

*TABLE 5-2: LOAD REGULATION*

| Full Load Voltage (V) | No Load Voltage (V) | Load Regulation |
|---|---|---|
| 5.074 | 5.185 | 2.19% |

As shown in Table 5-2, when the circuit is supplied by the nominal 5 $A_{rms}$ the load regulation for the circuit is 2.19%. This signifies good load regulation since ideally, the output voltage should not react to changes in the output current.

Another important performance measurement of DC-DC converter is line regulation. Line regulation is the ability of a supply to maintain constant output with varying input. For this circuit we measured the line regulations in terms of current out and current in as our input acts as a current source. The following equation was used to calculate Line Regulation.

$$Line\ Regulation\ = \frac{\Delta V_o}{\Delta V_i} * 100\%$$

To calculate the line regulation of our design, two cases were tested: one with the minimum expected 3 $A_{rms}$ current input and one with the maximum expected 5 $A_{rms}$. As listed in Table 5-3, the measured line regulation is .0022%. This signifies that the circuit has good line regulation since the output is not fluctuating with changes in the input.

*TABLE 5-3: LINE REGULATION*

| **Output Voltage at 5 Arms** | **Output Voltage at 3 Arms** | **Line Regulation** |
|---|---|---|
| 5.0738 | 5.0734 | 0.0022% |

# Chapter 6: Conclusion

The goal of this project is to design a power supply for an environmental detection system for a startup company called Perch Sensing. One of the main design focuses is harvesting the energy from the magnetic fields of the power lines. Aside from the circuit design for the power supply, a PCB was also designed for this project. Due to the COVID-19 pandemic, this project is entirely simulation-based using LTSpice.

From a high-level perspective, our project aims to convert an AC current source (current transformer output) to a DC voltage source (for the microcontroller). This presented several unique challenges that we had to overcome in various ways throughout our project such as the need to rectify a current source as well as regulating the output voltage of the power supply.

Based on the simulation results, our design had an output voltage peak to peak ripple of 36mV and was able to successfully supply a load of 15W. Through many design and simulation iterations, our project successfully fit the output voltage ripple requirements, output power consumption, and had less than 3% load and line regulations. Our design utilizes a varying input current simulating a current transformer from 800-1200A and provide 5V DC to reliably power a Raspberry Pi as well as associated sensors. In addition, the project is less than the component cost specification at a total of $253.68. Not included in this total is the cost of PCB fabrication and the coupled inductor which will need to be custom designed.

Although our circuit was able to meet all the specifications, the power supply's efficiency results were less than ideal. Further improvements can be made to improve the efficiency and robustness of our design. These changes are delineated next.

The main area of improvement for this design is with the efficiency of the whole circuit. While our DC-DC SEPIC converter reaches efficiencies between 73-79%, the circuit in its entirety has a maximum efficiency of 66.32% at 3 $A_{rms}$ and a minimum efficiency of 15.49% at 5 $A_{rms}$. These low efficiencies can be attributed to the high current supplied from the secondary side of the current transformer that must be shunted away from the power supply.

One possible method to improve this circuit is to use a current transformer with a different turns ratio. As shown from our simulation results, the circuit is more efficient at lower currents so it would be best to use a current transformer specifically with a lower secondary side current. Aside from improving the efficiency of the circuit, using a lower supply current to the circuit could possibly eliminate the need for a shunting mechanism at the input stage to prevent overcurrent. This not only reduces the physical size of the circuit, but it can also make the circuit safer overall.

Additionally, another improvement would be to find a different way to minimize the current going to the DC-DC converter. An optocoupler is currently used to divert current but there are concerns of the robustness of the chip over the lifetime of the device since a large amount of current is continuously being shunted. The circuit can be made more reliable, as well as more efficient by replacing the optocoupler with a solid-state relay rated for high currents. This is because the relay requires less input current, and thus input power. The relay is MOSFET-based rather than diode based and the quiescent current of the MOSFET involved would be inherently limiting and much lower than the current needed to activate the diode in the optocoupler.

Another recommendation for future work would be to use a different circuit simulator. It was necessary to observe the circuit at steady state throughout each design iteration and the simulation run time proved to be a challenge when collecting data. If the simulation speed were faster, more data could be collected and possibly more design iterations could be conducted. Furthermore, LTSpice did not offer very many solid-state relay models so to improve the efficiency of the power supply, testing different solid-state relays in hardware would be the best option to optimize this design. Although this circuit was tested multiple times on LTSpice, physical hardware testing may exhibit different results and part modifications may need to be made.

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# Appendix A. Analysis of Senior Project Design

**Project Title:** Power Line Coupling Power Supply Design

**Student's Name:** Janine Darato, Jeni Kawate, and Nicholas Marta

**Advisor's Name:** Taufik

- **Summary of Functional Requirements**

The fire detection system attaches to power lines and identifies fires using sensors. This power supply design project provides voltage to a microcontroller, which powers the grid of sensors. The high voltage power line powers the power supply and the power supply output's low DC voltage. The output bus is 4.5-6 volts and supplies constant voltage for the microcontroller and sensors to safely operate. The power supply power rating ranges from 9 to 16.5W and outputs 2-3A of current.

- **Primary Constraints**

The biggest constraint on the designing process was working around a current source input from the current transformer, rather than a typical voltage source input for the power supply. This affected efficiency calculations in LTSpice and requiring a shunting mechanism to be implemented as well. Furthermore, the deliverables of this project changed over time given the circumstances of the current pandemic. LTSpice schematics and a printed circuit board are the main deliverables since the project was completed virtually, rather than testing and populating the board.

- **Economic**

Our product has the potential to prevent lawsuits directed toward power distribution companies like PG&E, saving these companies money and saving the state of California money if it would have to bail these companies out. This product also has the potential to prevent billions of dollars of property damage throughout its lifecycle by preventing fires. One caveat with implementation includes companies such as PG&E charging their customers more because of implementation and maintenance of this fire detection system. This could change human and financial capital distribution and potentially enrage household communities.

The device uses power line energy, which may come from finite resources, such as fossil fuels and uses finite metals to construct. However, it has the potential to mitigate damages from forest fires or stop them from occurring all together, which gives the product the potential to save large swaths of nature. This impact could increase in coming years as the conditions of climate change worsens, these wildfire events are predicted to occur more frequently. Currently, Perch Sensing and Cal Poly senior project funds pay for the research and materials required for this project. The cost of the coupling inductor was not included in our BOM as it should be made by the next team working on the project. Factoring in the price of products we intend to purchase, and the 114 hours per person predicted to complete the project, the predicted development cost comes out to $13,846.78.

The system produces a communication signal that transmits to the utility company and fire department, alerting them of the location to handle the situation. The utility company profits because they save money by preventing damage to their property by attending to a fire as soon as it occurs. This project saves rather than earns money because it helps prevent damage caused by fires. Timing proves critical for this system because once a sensor detects smoke, it instantly notifies the utility company and fire department. This means the power supply must reliably always stay on.

As the device has its own power supply, the lifetime of the device should be 5+ years before requiring repair. Throughout this system's life cycle, benefits accrue when the system notifies utility companies of a fire with the exact location. This allows for utility companies to halt all power in the area and prevent damage caused by the fire. This results in cost benefits for utility companies and increases safety for the public. Utility companies must continually pay to power these devices as they check for fires. When active, the system retrieves power from the power line the utility company already owns, therefore maintenance costs involve maintaining the power line. Over time, costs also arise when utility companies need to replace sensors, or an accident occurs that damages the product. These maintenance operations range in cost from the price of an individual sensor to the cost of the entire project.

- **If manufactured on a Commercial Basis**

PG&E, Southern California Edison and San Diego Gas & Electric are the three main utility companies serving California and form much of our customer base. If manufactured on a commercial basis, we have four possible price ranges that depend on the number of units we make per year. As we buy more materials, the cost per unit decreases. The categories include 1-25 units, 26-500 units, 501-10,000 units, and 10,000+ units. PG&E alone has over 106, 681 circuit miles of distribution lines in California and assuming a device is placed every 20 miles, that would mean PG&E alone could purchase over 5,334 devices [10]. Therefore, we predict that we will sell 501-10,000 devices per year. Manufacturing 501-10,000 devices per year costs $250 per device. Each device costs $3000 and after subtracting additional costs for material and software, the gross margin equals $1949 per device. This results in the estimated profit per year within this category $976,449-$19,490,000. There are no additional estimated costs, as maintaining power lines already take place on a normal basis.

- **Environmental**

The main environmental impact of our product lies in the environmental damage it may prevent. If our project sells, it can mitigate much of this damage in the coming years. It could also save wildlife living in the area. However, this device relies on the magnetic fields produced by the transmission of electricity through power lines. If this electricity is not generated from renewable energy sources, it likely uses fossil fuels, such as oil, coal, or natural gas, which damage the environment. Environmental impacts associated with the manufacturing of this project stem largely from the components they use. Copper, steel, and aluminum are common metals that make up power lines and power supply components and may require environmentally unfriendly mining, refining and production methods. Components used in this project comply with the Restriction of Hazardous Substances Directive (RoHS) as harmful substances such as lead, and mercury are banned.

- **Manufacturability**

One of the main challenges for manufacturing lies in quality assurance across large quantities. The failure rate must not exceed a low threshold, otherwise our product cannot sell. This means each circuit and trace within the PCB must be tested thoroughly as well as the entire system. Component failures can also pose an issue and result in a malfunction of the device. Distribution may also pose challenges. This device may go to various locations across the state, so care must be taken so that the product remains intact when shipped. It is also important for technicians to ensure the device is assembled correctly. Additionally, for the product to be assembled cheaply we must assemble a certain threshold of products, which poses an issue in the beginning of the company’s lifecycle.

Since this project is a power supply, it is necessary to ensure that the noisy components such as the AC rectifying stage and the DC-DC power stage are placed farther away from the switching controller of the DC-DC converter when manufacturing the PCB. This is important because we also need to adhere to the size constraints of the project.

- **Sustainability**

Since the system hangs on a wire, it must endure multiple weather conditions such as ice, snow, rain, and fires. The power supply must withstand a temperature range from 0 degrees Celsius to 75 degrees Celsius to endure the full temperature range in California. This project proves sustainable in its use of resources because the power supply relies solely on power line energy, which already exists, and the customer maintains. In addition, the device uses an insignificant amount of power when compared to the delivered power of the power lines. Thus, our project will not alter the regular functioning of these lines and require additional resources outside of the power produced. Additionally, the devices continue to operate so long as the lines have adequate current.

We may upgrade the system with sensors for air quality and humidity to more accurately account for fire risk or find other environmental data. This may pose a challenge as the weight of the entire system cannot exceed 7 pounds. This may require the use of extra light sensors or a redesign of the original system to account for the extra weight. Customers must also maintain the product to ensure proper functioning, but this impact should prove minimal as the product has no moving parts to break down. However, the housing for the product may have to be maintained to account for weather damage.

- **Ethical**

To make our device ethically sound according to the utilitarian ethical framework, we avoid purchasing parts from manufacturers who unethically source their raw materials. The bad introduced by the exploitation of host countries for these materials and unjust labor practices would exceed the good of getting a lower price. Thus, according to the utilitarian framework, this would prove unethical.

Since this device is primarily for wildfire detection, it serves to notify utility companies of possible wildfire activity and subsequently, protects the public and the environment. The device must also be designed to keep lineman and professionals installing the device safe. This device intends to save much more money in lawsuits and damages than it costs. Thus, from a utilitarian perspective, it proves ethical. However, the cost associated with this may go to customers, and some customers may not reap the benefits. This unavoidable charge would limit these customer's freedom, which violates the golden rule as we would not want to be forced to pay for something that does not benefit us.

An ethical implication that can result from manufacturing is if only 98% of the batch proves safe but 2% proves a safety hazard. From a utilitarian approach, we would deploy the device despite safety concerns for the greater good. However, on a large manufacturing scale, 2% of devices manufactured could mean tens of thousands of devices that could potentially cause an accident.

The IEEE code of ethics regards the health, fair treatment, and welfare of individuals. This project is designed to improve general welfare and health. Below is an example of an IEEE criterion we meet by completing our project and an IEEE criterion we must take extra consideration to complete.

1.) to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment;

Since this device detects wildfires, it serves to notify utility companies of possible wildfire activity and subsequently, protects the public and the environment. However, to abide by this same code, the device must also be safe for the lineman and technicians that install it. Furthermore, this device only uses environmental sensors to detect wildfires. Therefore, the device abides by this code by not breaching the privacy of others.

2.) to seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, to be honest and realistic in stating claims or estimates based on available data, and to credit properly the contributions of others;

We must extensively test to ensure the safety of the device as it hangs from high voltage power lines. If any safety concerns arise, we must accurately document them.

- **Health and Safety**

The device prevents fires, which improves the safety of everyone in affected areas. However, installing the device may put people in danger for two reasons. Firstly, one would need to climb to heights of 55-200 [11] feet in the air to install the devices, secondly, they would need to be near high voltages. For this reason, we have a size and weight constraint for this project, so workers can install the device as quickly and efficiently as possible. The design of the device and of the power supply minimizes contact with the power line. To prevent any mishaps, part of the power supply design focuses on designing a protective circuit for the device to prevent any short circuits. The design generally increases the safety of communities by preventing forest fires.

- **Social and Political**

Various utilities companies have faced numerous lawsuits for fires they caused. Our project intends to ameliorate these issues and prevent the lawsuits associated. The stakeholders in this project include utility companies (such as PG&E, SCE, and SDGE), wildlife, communities under the jurisdiction of the power companies and insurance companies. This project could save wildlife, prevent communities in affected areas from losing their homes and save insurance companies from having to cover property damages. Power companies purchasing our product may treat customers unequally and only put the sensors in certain areas but charge all customers more to recoup the cost of the product.

Depending on the sensitivity of the sensors, the device could detect people smoking in the area and potentially send a false signal to the utility company of a fire on the area. This issue could cost the company money for contacting firefighters or sending workers to the location immediately. Perch Sensing is a primary stakeholder of our device as this forms part of their product. The success of their product largely depends on the reliability of the power supply, and at the same time, affecting the company image and reputation.

- **Development**

For this project, we discovered how inductive coupling works to get power from lines and how to scale down voltage in DC circuits. We also learned how to properly rectify AC signals to DC and the pitfalls to avoid in designing. Finally, we learned KiCad to design the PCB. Another resource referenced when determining our design process for this project is the paper [7], in which the authors document their own design steps and experimental results with their overhead transmission line harvesting system design and components. We found this paper while completing a literature search for this project. The literature search conducted also aided in the developmental process of our project as the bulk of our research focused on finding research papers and journals that focused on harvesting energy from power lines and on inductive coupling technologies.

- **Literature Search**

1. **Patent**

B Godard, “A vibration-sag-tension-based icing monitoring over overhead lines,” presented at IWAIS 2019, Reykjavík, Iceland, June 23-28,2019.

This source outlines a device very similar to our project. The device discussed hangs from a power line and measures accretion of snow or ice. Because the device discussed in this article hangs from a power line, the same size, noise, and weight constraints prove very similar to ours. By analyzing how Godard met these constraints, we can better equip ourselves to meet these constraints ourselves. The source reads logically sound and uses a variety of reliable sources. The proceeding uses peer reviewed sources such as several sources from the “IEEE Transactions on Power Delivery”, and conferences such as the “World Weather Open Science Conference”.

2. **Article**

W. B. Boast, "Transpositions and the Calculation of Inductance from Geometric Mean Distances," in *Transactions of the American Institute of Electrical Engineers*, vol. 69, no. 2, pp. 1531-1534, Jan. 1950, doi: 10.1109/T-AIEE.1950.5060330.

This article discusses how to calculate the inductance of a power line. This proves incredibly useful for our product, which uses coupling to get its power. Because we need to siphon power from the power lines themselves, it proves imperative to know all parameters of the power line, including inductance per unit length. The article may also help us find the inductance of our own lines. While this article was written a while ago, it discusses power lines, which have not changed significantly since the publishing of this article. The paper also proves the inductance per meter of a power line with incredible IEEE also posted the article, giving it some additional reliability.

### 3. Book

M. K. Iskander, “Static Electric and Magnetic Fields” in *Electromagnetic Fields and Waves*, 2nd Edition, Long Grove, IL, USA: Waveland, 2013, ch. 4,sec. 1-13, pp.347-433.

This book provides extensive information on how to determine the magnetic flux coming from current carrying wires. Additionally, it allows us to determine the self-inductance of wires and mutual-inductance. This helps us determine the inductive behavior of our own device as well as the mutual inductance between our device and the power lines. This proves crucial for getting power to our device. California Polytechnic State University uses this book in a couple of its major courses. As Cal Poly ranks as one of best undergraduate electrical engineering programs in the country, the school’s use of the book gives the source credibility. Additionally, over 300 other sources cite this book, giving it additional reliability. Finally, the book follows a logical progression of steps to prove each claim.

### 4. 2nd book

Taufik, *Introduction to Power Electronics*. San Luis Obispo, CA, USA: Lulu, 2020.

This book provides extensive information on Power electronics and potential issues that can arise from them, such as vampire power. This book specifically covers rectifier design, which proves central to our project. It also discusses various topologies and the advantages and disadvantages of each. This allows us to select a specific topology for our needs. California Polytechnic State University uses this book in its Power Electronics course (EE 410). As Cal Poly ranks as one of best undergraduate electrical engineering programs in the country, the school's use of the book gives the source credibility. The book also derives its claims and cites design advice given from companies successful in power electronics such as maxim integrated and Texas Instruments.

### 5. Datasheet

BALLUFF, "Inductive Couplers," BIC0054 datasheet, August. 2020.

This datasheet gives insight into the weights and dimensions of an inductive coupler, which gives us insight into the dimensions and weight we should aim for when designing our own Inductive Coupler. This datasheet proves particularly useful because it has an output voltage rating of 24V, the voltage we want from the line. The output current, however, is not close to our desired current. This datasheet outlines a product sold by Balluff; a company valued at hundreds of millions of dollars. The success of the company suggests accuracy of their datasheets. The sheet itself also has all standard measurements that make sense. Finally, the product abides by CE, EAC and WEEE standards.

### 6. Article

L Guilherme, "Coupling for Power Line Communication: A Survey," Communication. vol. 32, no. 1, pp.1-12, December. 2016 [Online]. Available: https://www.researchgate.net/publication/314236133_Coupling_for_Power_Line_Communication_A_Survey

This article discusses inserting or receiving signals from power lines using coupling. Currently, we plan to use wireless transmission, but using a coupling strategy to take advantage of the power lines may prove more effective. The article discusses the challenges that come along with this method, including dealing with impedance matching, signal loss and signal filtering. This article cites 138 sources, mainly conference proceedings and peer reviewed journals. It also makes electronic and mathematical sense. Forty other papers also cited this article. While not a high number, it shows that the academic community uses the paper. The main author has a doctorate in electrical engineering, the subject matter of the paper.

### 7. Datasheet:

life.augmented, "Power line communication AC coupling circuit," STEVAL-ZPLM01CPL datasheet, June. 2017.

This datasheet outlines a potentially useful product for our design. If we use over-the-line communication, this product could test our system for proper operation. Even if we do not use this method of communication between devices, the way the device couples to the power line have use in designing out coupling power supplies. The datasheet includes a schematic for doing this. This datasheet outlines a device produced by STMicrelectronics, a Swiss semiconductor and electronics company worth several billion dollars. The success of the company points to success in their products and documentation, giving validity to both the design in the datasheet and the documentation in the datasheet itself. Additionally, it includes all pertinent information for a device like this. Finally, ST updates its datasheets to account for inaccuracies.

### 8. Article

J.L. Lilien, "Real-Time Ampacity Monitoring with Ampacimon," University of Liège, Liège, Belgium, October. 10, 2020. [Online]. Available: http://www.ampacimon.com/wp-content/uploads/2015/09/Features-EN.pdf

This article discusses an ampacity monitoring system called Ampacimon. This device would prove incredibly useful in determining the current flowing through various power lines because it would allow us to know what magnetic flux comes from these lines. Currently, no one on the team has found reliable information on the amperage of power lines in different locations. Thus, we may have to test this information for ourselves. A professor from Cal Poly, Professor Poshtan, suggested this article. As he teaches at one of the best undergraduate EE programs, this gives the article some reliability. The article also has logical flow and supports its statements and the author, Lilien, has a PHD in EE and teaches transmission and distribution of electrical energy, the subject of this paper.

### 9. Website

S Anthony. "German student creates electromagnetic harvester that gathers free electricity from thin air" Extremetech.com. https://www.extremetech.com/extreme/148247-german-student-creates-electromagnetic-harvester-that-gathers-free-electricity-from-thin-air (accessed Oct. 10, 2020).

This article helps my research because it covers a device that gathers power via inductive coupling and provides an introduction to the subject matter, which proves massively helpful in this preliminary search. This article helped me refine my search on this subject matter and led to me finding many of the sources listed above. While the author, Sebastian Anthnony, does not possess an EE degree, he covers a product that is fully developed and in use. This proves the concept discussed in the article. Additionally, the article has had high traffic and almost 200 comments, none of them arguing with the article and most of them corroborating this information. The article reads logically sound and discusses the laws of physics correctly as well.

### 10. Website

"Rectifiers." DynaPower. https://www.dynapower.com/rectifiers/ (retrieved October 10, 2020)
This article discusses rectifiers, which constitutes one of the main pieces of our project as we need to convert AC to DC. It also discusses rectifiers from an industrial perspective, listing what qualities designers want in general and what can pose issues. For example, it discusses heat generation and the problems it can cause as well as how to fix it with clean contacts. It also describes maintenance of rectifiers. Getting a company perspective specifically also proves helpful as we plan to make a product and start our own company around this. While the page gave no specific author, Dynapower, the company responsible for the page, has a net worth of several million dollars and focuses on energy handling and storage. The article reads logically and electrically sound given what I have learned in power electronics. The company also works with rectifiers specifically, furthering their reputability. Finally, their products meet IEEE standards, and the U.S. military uses their products, showing they provide good design.

# Appendix B. Project Timeline

Figure 0-1 delineates our milestones during Winter quarter. Figure 0-2 delineates our milestones during Spring quarter. Although our timeline includes a hardware build and testing phase, due to COVID-19 we were unable to complete this part of the project.

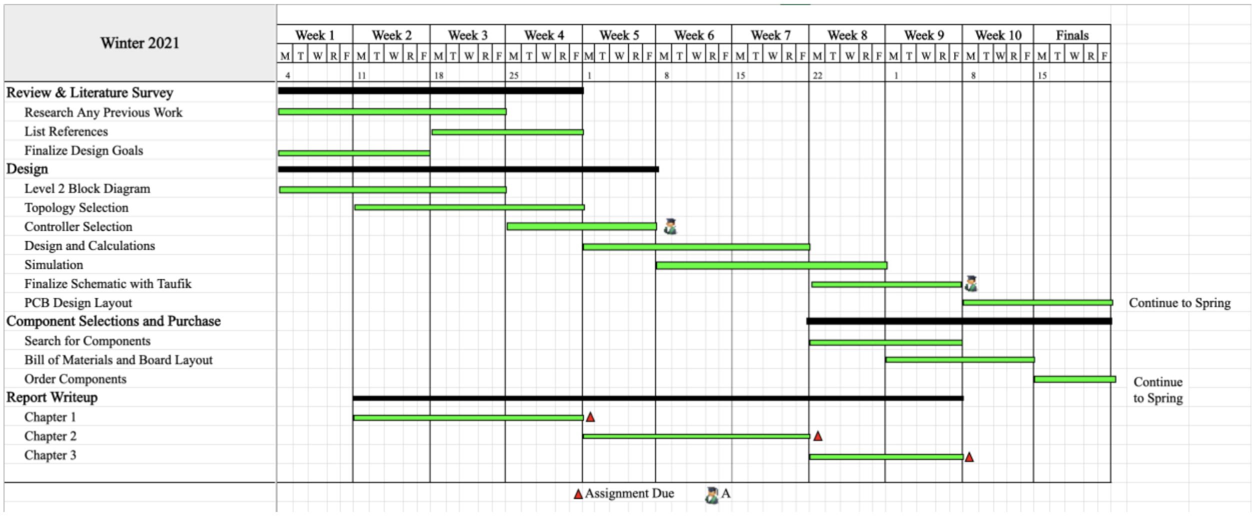

*FIGURE 0-1: WINTER QUARTER GANTT CHART*

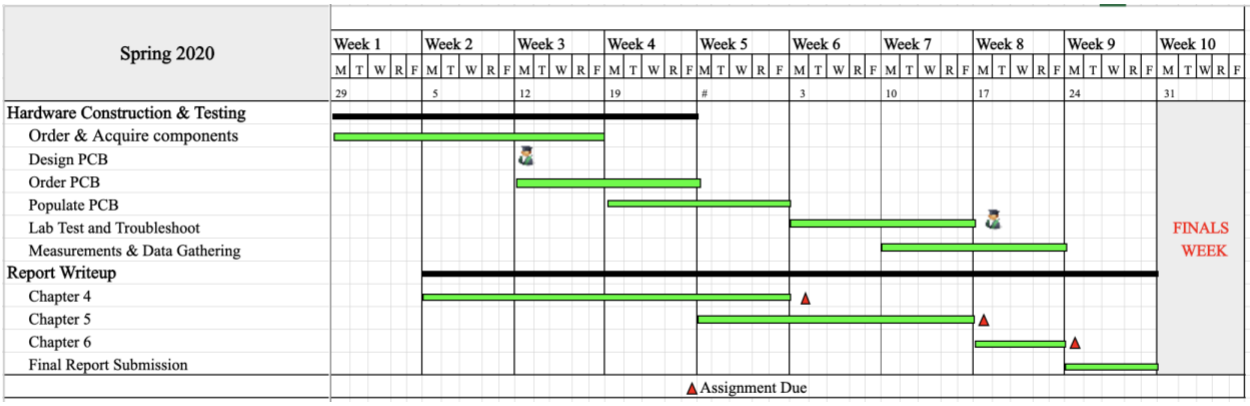

*FIGURE 0-2: SPRING QUARTER GANTT CHART*

# Appendix C. Bill of Materials

The bill of materials is a list of all non-ideal components of the power supply, except the current transformer, inductors, and PCB manufacturing costs.

*TABLE 0-1: BILL OF MATERIALS*

| **Count** | **RefDes** | **Value** | **Description** | **Size** | **Part Number** | **Manufacturer** | **Cost Per Unit** | **Cost** |
|---|---|---|---|---|---|---|---|---|
| 1 | R1 | 82 KΩ | Thick Film Resistors - SMD CRGP 2512 82K 1% SMD Resistor | 0.55mm x 6.5 mm x 3.2 mm | CRGP2512F82K | TE Connectivity | $0.46 | $0.46 |
| 1 | R2 | 32 KΩ | Thin Film Resistors 32K ohm 0.1% 50 ppm High-Precision | 0.45 mm x 1.6 mm x 0.8 mm | RT0603BRE0732KL | Yageo | $0.50 | $0.50 |
| 1 | R3 | 100 KΩ | Thin Film Resistors 0.1% 1210 .25W AEC-Q200 | 0.6mm x 3.2mm x 2.5mm | RN73R2ETTD1003B25 | KOA Speer | $0.98 | $0.98 |
| 1 | R4 | 33 KΩ | Thick Film Resistors 0.4watt 33Kohms 1% 100ppm | .45 mm x 2 mm x 1.25 mm | RCS080533K0FKEA | Vishay | $0.25 | $0.25 |
| 1 | R6 | 332 KΩ | Thick Film Resistors 332K ohm 1% 0.25W | 0.6 mm x 3.2 mm x 1.6 mm | HV732BTTD3323F | KOA Speer | $0.48 | $0.48 |
| 1 | R7 | 20 Ω | Thin Film Resistors 0.1% 1210 .25W AEC-Q200 | 0.6 mm x 3.2 mm x 1.5 mm | RN73R2ETTD20R0B25 | KOA Speer | $0.98 | $0.98 |
| 1 | R8 | 5 Ω | Thick Film Resistors 20W 5ohm 1% | 4.5 mm x 10.1 mm | D2TO020C5R000FTE3 | Vishay | $12.72 | $12.72 |
| 1 | C1 | 6.8nF | Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 6800pF 0603 10% 10V MLCC | 0.8 mm x 1.6 mm x 0.8 mm | 885012206013 | Wurth Electronik | $0.10 | $0.10 |
| 1 | C2 | 47pF | Multilayer Ceramic Capacitors MLCC - SMD/SMT WCAP-CSGP 47pF 0603 5% 10V MLCC | 0.8 mm x 1.6 mm x 0.8 mm | 885012006006 | Wurth Electronik | $0.10 | $0.10 |
| 1 | C3 | 4.7uF | CAP CER 4.7UF 4V X5R 0201 | 0.8 mm x 1.6 mm x 0.8 mm | GRM035R60G475ME15 | Murata | $0.44 | $0.44 |
| 1 | C4 | 3.9mF | Aluminum Electrolytic Capacitors - Radial Leaded WCAP- | 31.5 mm | 860010480024 | Wurth Electronik | $1.98 | $1.98 |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | ATG8 3900uF 25V 20% Radial |  |  |  |  |  |
| 1 | C5 | 10uF | CAP CER 10UF 25V X5R 0603 | 0.8 mm x 1.6 mm x 0.8 mm | GRM188R61E106KA73 | Murata | $0.34 | $0.34 |
| 1 | C6 | 330uF | Aluminum Organic Polymer Capacitors WCAP-PSLP 6.3V 330uF 20% ESR=20mOhms | 6.6 mm x 6.6 mm x 5.8 mm | 875105144010 | Wurth Electronik | $0.56 | $0.56 |
| 1 | C7 | 100u | ±20% 6.3V Ceramic Capacitor X5R 0402 (1005 Metric) | 1 mm x 0.5 mm x 0.5 mm | GRM155R60J106ME15 | Murata | $0.19 | $0.19 |
| 1 | C8 | 100uF | Aluminum Organic Polymer Capacitors 25V 100uF 20% ESR=14mOhms | 6.7mm x 5.7mm | A768EB107M1ELAE036 | Kemet | $0.47 | $0.47 |
| 1 | C9 | 100nF | Multilayer Ceramic Capacitors MLCC - SMD/SMT .1UF 6.3V 10% 01005 | 0.4mm x 0.2mm x 0.2mm | GRM022R60J104KE15 | Murata | $0.13 | $0.13 |
| 1 | C10 | 2.2uF | Multilayer Ceramic Capacitors MLCC - SMD/SMT 0603 2.2uF 6.3volts X7R 20% | 1.6mm x 0.8mm x 0.8mm | GCM188R70J225ME22 | Murata | $0.30 | $0.30 |
| 1 | D1 | - | Schottky Diodes & Rectifiers | 330mm x 24mm | RBR30NS30A | Rohm | $1.48 | $1.48 |
| 1 | D2, D3, D4, D5 |  | Bridge Rectifiers 10A 600V Standard Bridge Rectifier | 25.3 mm x 13.4 mm x 10.6 mm | TS10KL60HD3G | Taiwan Semiconductor | $0.61 | $0.61 |
| 1 | Q1 |  | MOSFET 12V 25A 3.5W 3.0mohm @ 4.5V | 4.9mm x 6mm | Si4838DY | Vishay/Siliconix | $1.49 | $1.49 |
| 1 | U1 | - | Switching Controllers No Rsense DC/DC Controller Boost, Flyback & SEPIC | 4.9mm x 3.0mm | LTC1871 | Analog Devices | $6.36 | $6.36 |
| 1 | U2 | - | LDO Voltage Regulators 200mA Programmable 2-Terminal Current Source or Linear Regulator | 0.27mm x 0.53mm | LT3082 | Analog Devices | $4.02 | $4.02 |
| 1 | U3 | - | Triacs 400V .8A Sensing 10-10-10-20mA | 10mm x 29mm | L4X8E8 | Littelfuse | $0.40 | $0.40 |
| 1 | U4 | - | Triac & SCR Output Optocouplers 6Pin800V Optocoupler Zero Cross Triac Dr | 3.53mm x 8.89mm x 6.6mm | MOC3081SVM | ON Semiconductor /Fairchild | $1.34 | $1.34 |
| **Total Cost** |  |  |  |  |  |  |  | **$36.68** |