# Economic Overnight Smart Outlet

ECE 445 Project Design Document Check

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# 1. Introduction

## 1.1 Problem

Real-time pricing in ISOs, such as those in the Midwest, Texas, California, New England, and New York, provides frequent differentials in electricity prices throughout the day that can be taken advantage of. Currently, most electronic users will charge devices at economically inopportune times. Whether that be needlessly charging during the day to “top off” or companies charging devices at the end of a workday, they miss out on the periods of minimal electricity prices. While this may seem minor, the peak price of electricity compared to the minimum prices can feature variations of up to 70%. With price agnostic charging, this results in unnecessary costs for those who charge devices.

While there do currently exist smart chargers which charge during nightly hours, these do not actively monitor electrical prices posted by ISOs. If a price spike were to occur, they would continue to charge regardless, thus incurring unnecessary costs. As the recent Texas winter price surge proved, these spikes can be dramatic and potentially expensive to unsuspecting consumers.

## 1.2 Solution

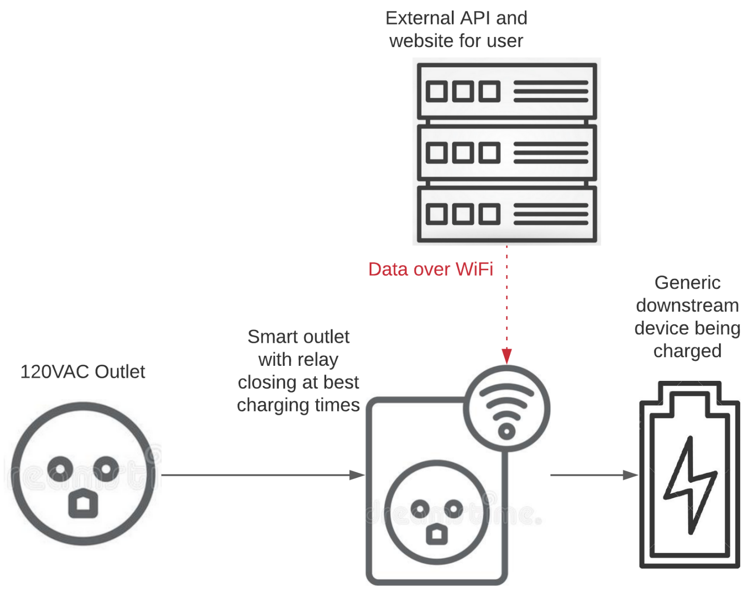
We will create a device that can fetch real-time prices from regional ISOs and enable charging when prices are lowest. Our primary application will be centered toward warehouse electric vehicles using high-capacity, fast-charging lithium ion batteries, limited to 120 V single-phase input charging. Such vehicles include forklifts, cleaning machines, and golf carts. This same principle scales for large commercialized applications requiring high-capacity batteries, resulting in an even greater potential savings with the increased economy of scale.

The “lowest price” of a potential charging period will be determined by factoring in common utility rate distributions with the real-time fetched prices. That is, typical real-time price curves reach their minimum rate at approximately 10:00 p.m. until 4:00 a.m. the next day. This period is generally preceded by a steep fall in electricity price, as local maximums occur at around 6:00 to 8:00 p.m. [1] . The viability of our solution rests on its ability to recognize when this period of minimum price points has been reached.

We will build a smart outlet for small EVs and commercial applications that utilize high capacity lithium batteries. Currently, customers charge these devices whenever they plug them in and do not exploit maximum savings potential from the real-time electricity market nor do they have any way to quickly respond to dramatic price spikes. Our product will resolve this by charging overnight at the nightly minimums ensuring that customers save the most possible money over a given charging period. The “best time” charging algorithm will also avoid price spikes should they occur during the charging period. Extrapolated over the product's lifetime, the outlet will recuperate it’s cost, profiting the user in electricity savings.

While there are smart appliances that utility companies are trying to push for, these are not generic devices that can be applied to any application. Since ours will simply be a 120VAC outlet that enables charging during low cost times, this keeps the product robust and highly flexible in how users can use it. Essentially anything that charges overnight can benefit from this product.

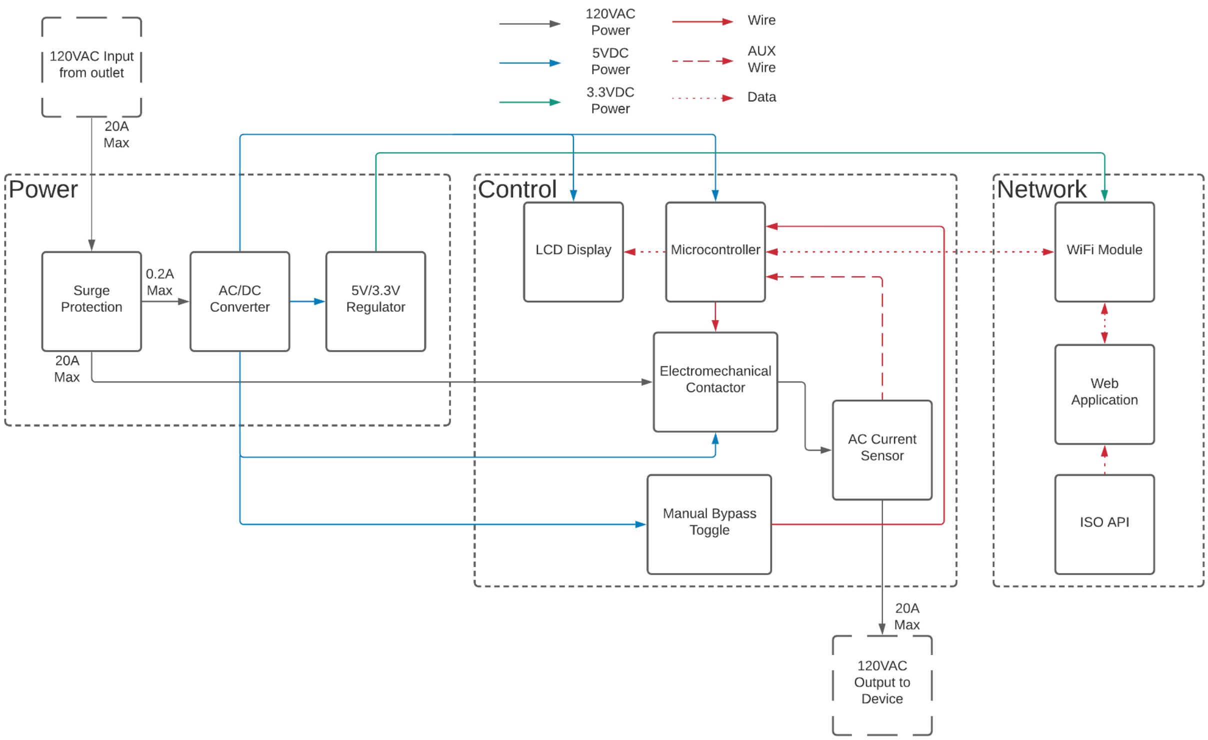
# 2. Visual Aid



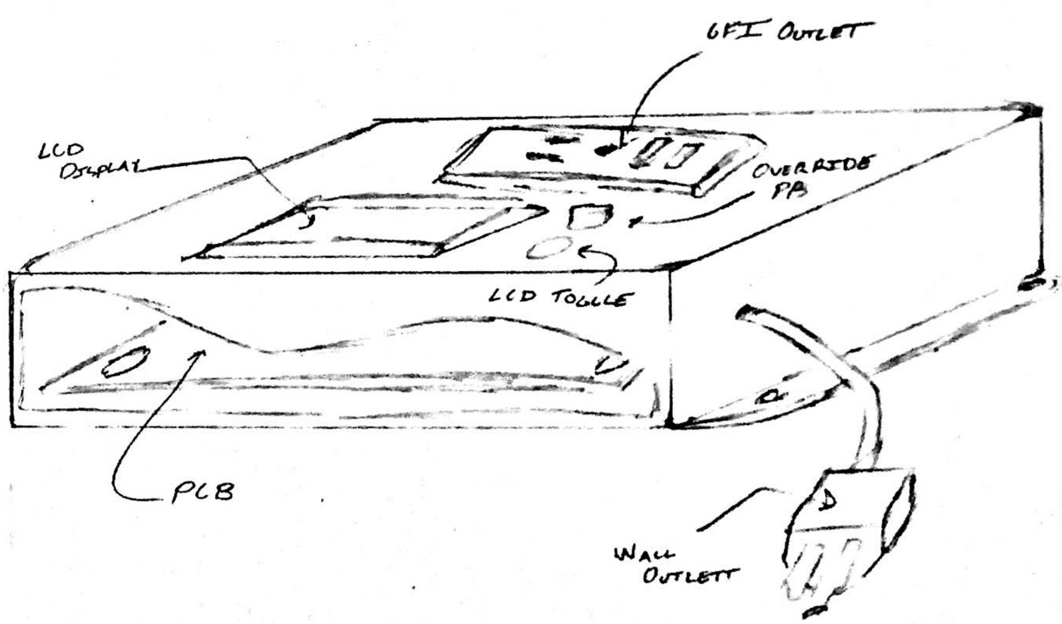

# 3. High Level Requirements

- The state of Charge (SoC) of the battery of the device being charged must be greater than 90% by the user-determined “charge by” time. This need supersedes price savings.
- The user’s “profit” will be defined as the savings in electricity when comparing charging at the end of the day (5:00 p.m.) versus charging when night prices are at their minimum. Should this profit be >20% over the device lifetime of about 3 years, we can deem that it makes economic sense to utilize the device.
- The outlet must be able to react to real-time energy cost data by pulling information from the ISO API. In ideal conditions, the outlet should be able to pull the cost data every five minutes and begin charging the device once price levels have plateaued to their minimums. Charging will halt if a price spike of >2x average nightly cost is detected.

# 4. Block Diagram




# 5. Physical Design



# 6. Requirements and Verification Tables

## 6.1 Power

The power components will allow all of the control components downstream to run off of the 120 VAC outlet connection. This will be accomplished through a 120VAC/5VDC power inverter outputting up to 300mA. Both the 120VAC input and 5VDC output will be accompanied by a surge protector, which will short out voltage spikes and dissipate inrush current.

### 6.1.1 Control Power Converter

The power converter will be a 10:1 step down transformer to bring the 120VAC input to 12VAC followed by a full bridge rectification. This rectified 12VDC is then passed into a linear regulator to bring it to a steady 5VDC.

| **Requirements** | **Verification** |
| --- | --- |
| 1. The converter must be able to step down 120VAC +/-10% to 5.0VDC +/-5%.<br>2. Converter must be able to safely handle a continuous current load of 300mA from the 5V output.<br>3. Maintain temperature below 125°C | 1.<br>A. Use AC power supply to vary input from 108VAC to 132AC over the course of 10 seconds. Use a multimeter to ensure output remains within desired bounds.<br>2.<br>A. Use electronic load to simulate current draw of 300mA. Leave for 15 minutes.<br>B. Verify with a multimeter that the output voltage remains within bounds.<br>3.<br>A. During test 2, use an IR thermometer to ensure devices stay below 125°C. |

### 6.1.2 Input Surge Protection

The input 120VAC will be protected via a MOV rated for 110% of 120VAC with protection shorting the input at ~340VAC.

| **Requirements** | **Verification** |
| --- | --- |
| 1. The surge protector must be able to sustain 3 voltage spikes lasting 1ms per year over 5 years with only a 10% increase in clamping voltage. | 1.<br>A. Use a signal generator to create a 340VAC pulse lasting 1ms. Repeat this after MOV has cooled to within 10°C of room temperature as verified with an IR thermometer. Do this 5 |

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| 2. The surge protector should have a rapid response time of less than 100 ns. | times.<br>B. After 1A, subject MOV to 1mA with current supply and ensure MOV voltage drop is within 185-225V with a multimeter.<br>2.<br>A. Use an oscilloscope during the first test of 1A to capture the current response of the MOV. Verify that once voltage spike passes 340VAC, the MOV draws 63.2% (1/e) of maximum observed current. |

## 6.2 Control

The control subsystems will receive data from the network subsystems as well as probe the downstream devices for SoC status. It will be powered by tapping the wall outlet and converting it down to 5VDC. Using API price data and estimations on battery state of charge, the control will determine when to turn the relay on/off to begin charging at the most economical times. It will also use the data to provide the user a display of savings over time to allow users to observe the performance of the device.

### 6.2.1 Power Contactor

This contactor will act as a NO on/off switch which allows the 120VAC, up to 20A, to pass through the outlet to any downstream connected devices. It will be an electromechanical relay where the coil will be energized from the microcontroller output signal, thus allowing the microcontroller to determine when to switch on/off.

| **Requirements** | **Verification** |
|---|---|
| 1. Temperature at 20A draw stays below 120°C<br>2. Relay must switch on with a >=100mA coil current. | 1.<br>A. Enable coil with a 120mA current source. Verify relay is engaged with continuity test with a multimeter Use a 6 ohm power resistor with a 120VAC voltage source to push 20A through relay contact for 10 minutes or until temperature reaches steady state. Verify with an IR thermometer that the relay is below 120°C.<br>2.<br>A. Using a voltage source, activate the relay circuit using a 5V node. Test coil current with current probe. Ensure that the relay engages using a continuity test with a multimeter. |

### 6.2.2 LCD Display

The LCD display will be used to highlight information about the current energy price, which will be taken from the ISO API, and the current day's savings, which will be calculated using the prices at all times in which the device is charging subtracted from the price at the of the day when the device was plugged in for the same amount of charging time.

| Requirement | Verification |
|---|---|
| 1. The LCD display must receive and display data from the microcontroller. | A. Connect the LCD display to the microcontroller using SPI. Verify that the LCD is capable of displaying exactly the following: "SAVINGS \n $XXX.XX", and "PlanStrt \n XX:XXx". |

### 6.2.3 AC Current Sensor

The AC current sensor will provide information regarding the battery's charging status. Namely, when the AC current is below an experimentally determined threshold, the device will consider the battery to be fully charged and will halt the charging process. Similarly, the sensor will be configured to recognize positive jumps in current, indicating that a battery has been plugged into the power converter and is ready to be charged. A toroidal non-invasive current sensor that emits an analog voltage reading will be selected to avoid overcurrent damage to the device.

| Requirements | Verification |
|---|---|
| 1. The AC current sensor must be able to interface with the Microcontroller via an analog or digital interface. For now, we will assume it is capable without a converter.<br>2. The sensor must be able to recognize AC current values of up to 20A.<br>3. The sensor must be compatible with a 60Hz grid operating frequency. | 1.<br>A. Provide DC bias for the -1 to 1V output voltage of the current sensor, and connect this to the analog input of the microcontroller. Connect a voltmeter to the biased signal and verify that the output signal stays between 0V and $V_{cc}$ of the microcontroller for a signal with 20A AC.<br>2.<br>A. Connect the non-invasive current probe to an AC current source (e.g. the model found in ECEB4024). Test current peak-to-peak values of 10, 20, 30, 40, and 50A.<br>3.<br>A. Clamp the non-invasive current probe to a functioning wire/extension cord connected to a functioning US wall outlet. Verify with an AC voltmeter that a voltage potential is being |

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| | created. |

### 6.2.4 Microcontroller

The microcontroller will perform on-board computations and communication with peripherals and sensors. Once a control scheme is fully matured and required computational power has been determined, a processor will be chosen. High-level computation and communication requirements are detailed below.

| Computational Requirements | Verification |
|---|---|
| 1. The controller must be able to perform an SoC estimation algorithm ("Coulomb counting" or "Kalman Filter").<br>2. The controller must be able to perform approximations for charge finish time (with +/- 1 hour accuracy). | 1.<br>A. Load the Kalman Filter C Code to the microcontroller and verify using the terminal monitor of the Arduino software that the Kalman filter is updating its discrete time steps and storing modeled parameters to device memory without overloading the microcontroller storage space.<br>2.<br>A. Run Matlab Simulink simulations with actual parameters representing a laptop charger, golf cart charger, and electric forklift charger using kalman filter block with time intervals equal to that of microcontroller constraints (e.g .1s). Verify that within 0.5 hours of plug in time the Kalman filter approximation was accurate to within 1 hour of the final charge completion time. |

| Communication Requirements | Verification |
|---|---|
| 3. The controller must be able to send charger usage data to the LCD display.<br>4. The controller must be able to send and receive data to the peripheral WiFi module.<br>5. The controller must be able to read 0-1V analog readings from the current probe. | 3.<br>A. Connect the LCD display to the microcontroller using SPI. Verify that the LCD is capable of displaying exactly the following: "SAVINGS \n $XXX.XX", and "PlanStrt \n XX:XXx".<br>4.<br>A. Connect the Wifi module to the microcontroller using I2C. Verify on the Arduino software print screen using a test program that wifi connection has been achieved.<br>5. |

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|---|---|
| | A. Connect the non-invasive current probe to an AC current source (e.g. the model found in ECEB4024) and to DC biasing circuit. Test current peak-to-peak values of 40A on current source and verify on Arduino software print screen that sensor voltage output values are being read by the microcontroller. |

## 6.3 Network

The network subsystems will connect the device to a web application and the ISO API using a WiFi module. These subsystems will transmit data among each other, with the WiFi module serving as a link to the microcontroller.

### 6.3.1 WiFi Module

The WiFi module will be used to gather real-time cost data from the ISO API as well as to transmit data regarding times in which the device is charging to the web application, which will showcase visualizations of cost savings over time.

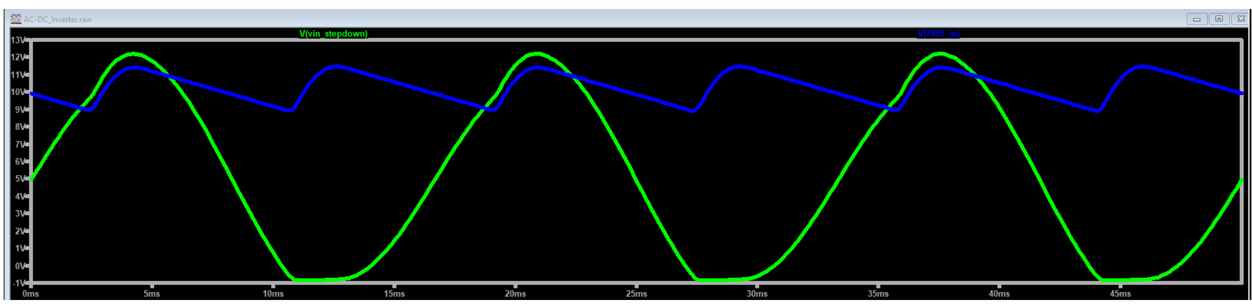
| **Requirements** | **Verification** |
|---|---|
| 1. The module must be able to interface with the microcontroller and web application and receive and send data.<br>2. The module should send charging time data to the web application at a minimum of once per day, after the connected device has finished charging and has been disconnected. | 1.<br>A. Send any number from the microcontroller to the WiFi module and send this signal from the WiFi module to the web application. Check that the signal appears on the web application page.<br>B. Send any number from the web application to the WiFi module and send this signal from the WiFi module to the microcontroller. Check that the signal has been received by the microcontroller using its output pins.<br>2.<br>A. After a charged device has been disconnected, check the visualizations on the web application and ensure that the current day's charging price comparison has been added. |

### 6.3.2 Web Application

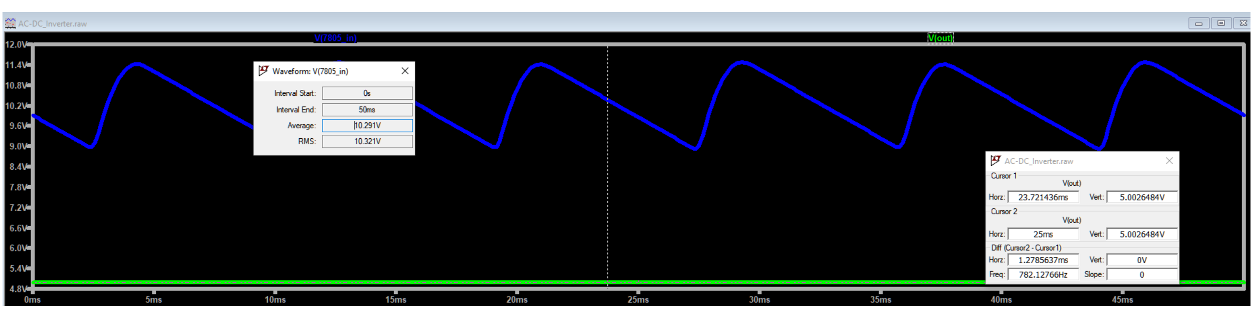
The web application will allow the user to input preferences, such as the time of day they need their device to be charged by. It will also display visualizations of cost savings over time, which will utilize the ISO API and data from the WiFi module to show actual costs compared to maximum costs of charging for each day.

| Requirements | Verification |
|---|---|
| 1.The web application should allow for a user to set preferences regarding the device's charging patterns and should send these preferences and any updates to the device upon entry.<br>2. The application should display visualizations of the amount saved each day over time. The charging time data needed for this will be received from the WiFi module. | 1.<br>A. Set the charge by time to a time within an hour of the current time and connect the device to be charged. The device should start charging instantly if its battery is low, regardless of the current price.<br>2.<br>A. After a charged device has been disconnected, check the visualizations on the web application and ensure that the current day's charging price comparison has been added. |

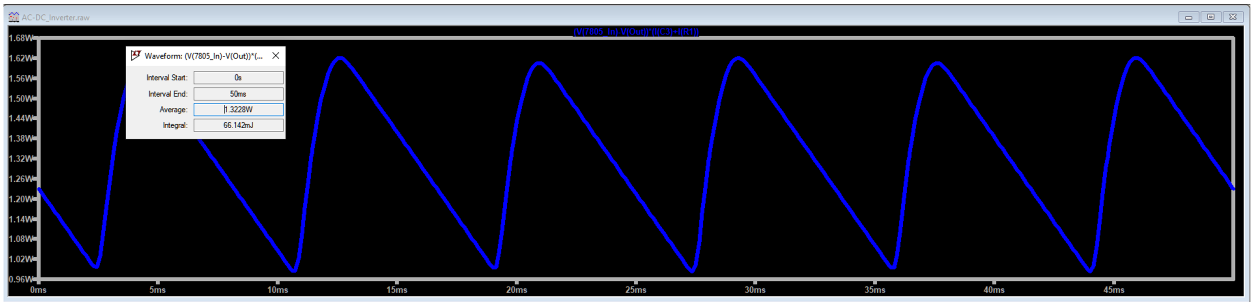
# 7. Plots



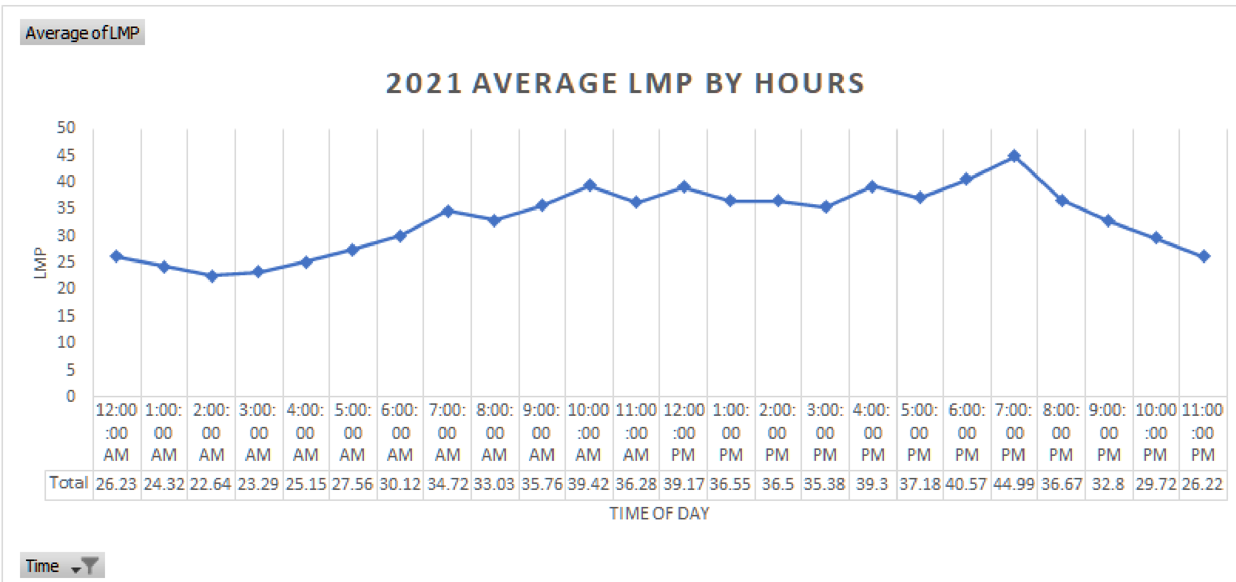

*Plot 1: 12VAC stepped down (green) and full rectified and filtered 10VDC output (blue)*




*Plot 2: 10V DC input to 7805 regulator (blue) to steady 5VDC output (green)*

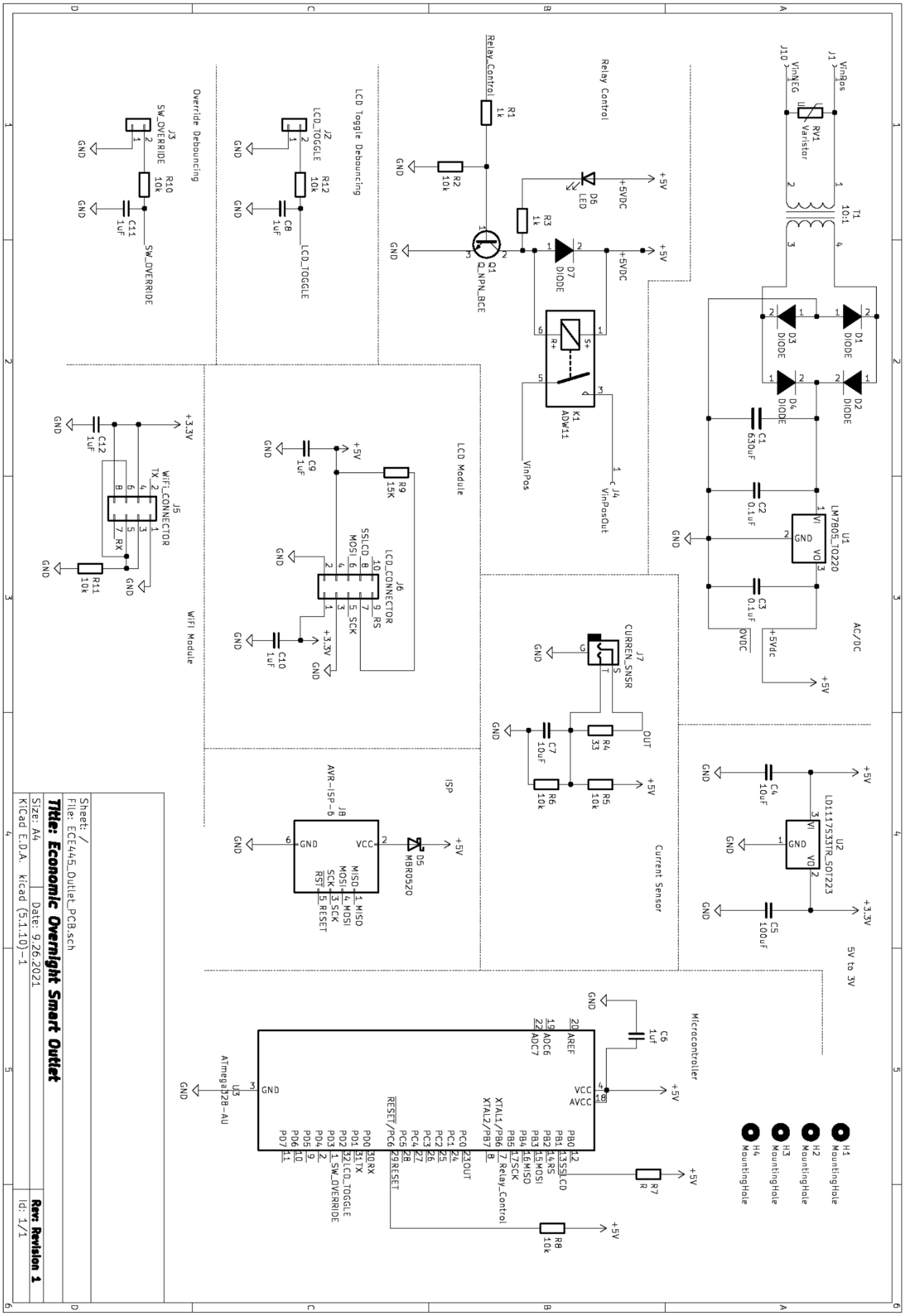



*Plot 3: Power dissipated across 7805. Average is 1.3W.*



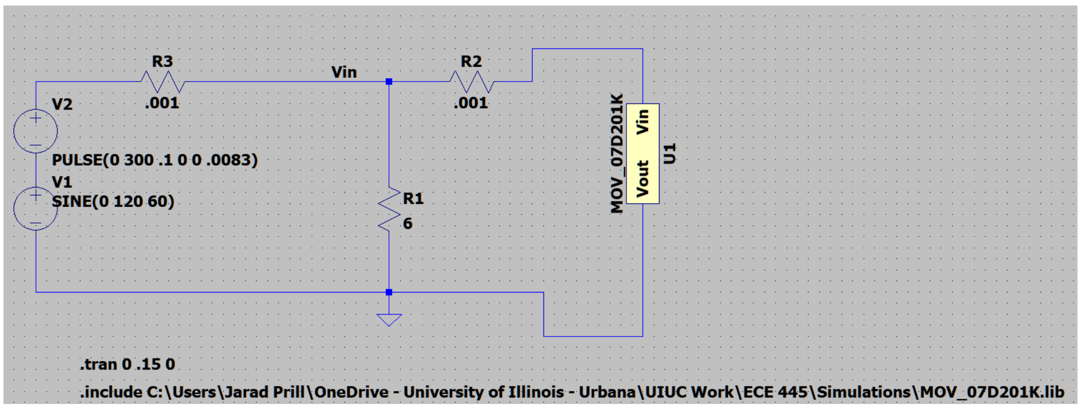

*Plot 4: Average Illinois LMP prices in 2021 by hour*

# 8. Circuit Schematics



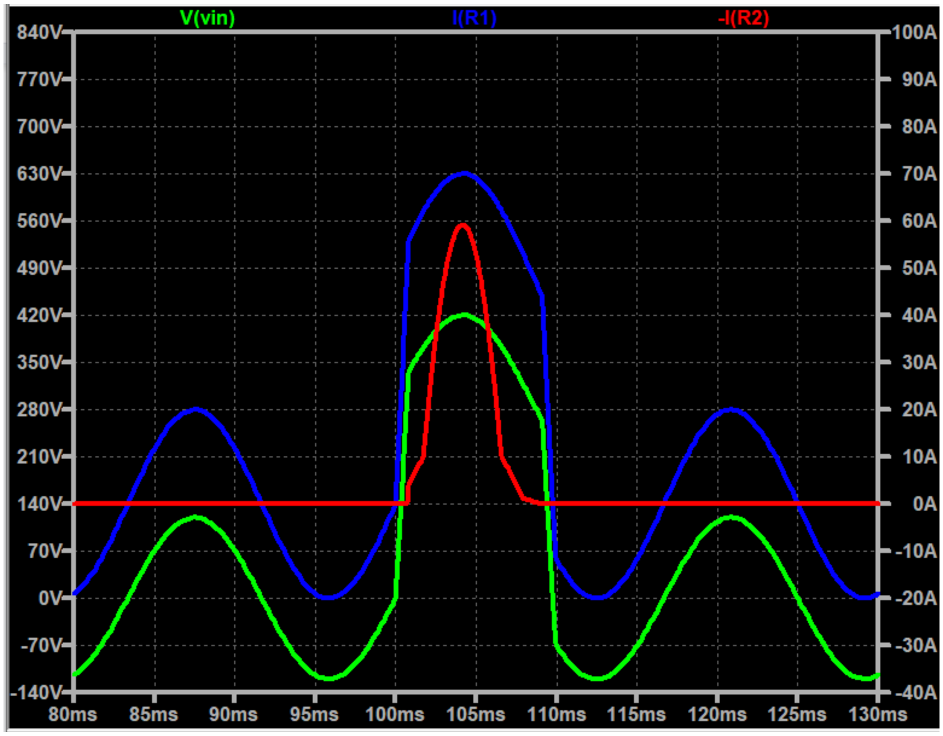
# 9. Tolerance analysis

Since our device will be handling downstream devices, we must ensure that we can safely and effectively handle voltage surges in the line. For this, we refer to NEC code 230.67, which requires a type 3 SPD. To meet this, we will use a permanent MOV installed immediately across the outlet input terminals. To find a well rated MOV, we will assume we are providing 120VAC at full load 20A when an additional 300VAC surge appears lasting 1ms. The MOV must keep the current to the devices below 500% 20A, or 100A. The justification for this is that for short spikes such as these, devices are rated for several multiples of their full load due to the surge not lasting a significant amount of time. See the below simulation results.




*Simulation circuit using Spice model of MOV 07D201K provided by Bourns Inc.*

This simulation has V1 as a normal 120VAC 60Hz source. Then, V2 creates a 300VAC surge that lasts for 0.0083ms. Note that the 0.0083ms was chosen so we could see the MOV over a half period.




*Simulation waveform. MOV current (red), input voltage (green), load current (blue)*

We can see that during the spike, the MOV resistance drops as it reaches its clamping voltage (340V) and will allow significant current to flow through itself, thus allowing the load current to remain below 70A. This means that the MOV can successfully prevent extreme current spikes being pushed through downstream devices. Due to the nature of the MOV taking large amounts of current, the lifetime of the surge protection is limited.

# 10. Safety & Ethics

The team will ensure customer data privacy in accordance with the ACM Code of Ethics principle 1.6, “Respect privacy,” by enabling collecting only relevant and necessary data and limiting access to this information [2]. The information to be collected will be user-inputted data about the time of day their device needs to be fully charged by and information about the user’s ISO location and their device’s charging times and energy costs at these times.

Similarly, the team will strive to ensure that the safety and wealthfare of the device’s user is held paramount, as stated in the 7.8 IEEE Code of Ethics [3]. Given the nature of the device, poor power system conversion and excessive battery charging could present potential electrical and heat hazards, respectively. If the testing or simulation of the device reveals that it exacerbates these hazards, changes to the design will be made to curtail the potential danger. Of particular note is OSHA 1926.44(b)(1), which specifies that "battery charging installations shall be located in areas designated for that purpose” [4]. As the device is intended for commercial and industrial applications, the team will strive to ensure that users of the device will not be encouraged to relocate their charging infrastructure to a non-charging-specific location in order to accommodate the device.

Following NEC code 210.8 [5], since our 120VAC outlet will potentially be installed in outdoor environments due to the general mobility of the product we will implement a GFCI outlet for the user. This will prevent ground faults from potentially harming personal operating a device connected to the outlet

# 11. Citations

[1] AEP Energy. “Real-Time vs. Day-Ahead Pricing.” AEPEnergy.com. [Online]. https://www.aepenergy.com/blog/december-2017-edition/ [Accessed: Sep. 16, 2021].

[2] “ACM Code of Ethics and Professional Conduct.” ACM.org. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: Sep. 16, 2021].

[3] IEEE Board of Directors. “IEEE Code of Ethics.” IEEE Code of Policies, Section 7 - Professional Activities (Part A - IEEE Policies). [Online]. June 2020. https://www.ieee.org/about/corporate/governance/p7-8.html. [Accessed Sep. 16, 2021].

[4] United States Department of Labor. “OSHA 1926.441 - Batteries and Battery Charging.” osha.gov. [Online]. https://www.osha.gov/laws-regs/regulations/standardnumber/1926/1926.441. [Accessed Sep. 16, 2021].

[5] National Fire Protection Association. “Article 210: Branch Circuits ” nfpa.org. [Online]. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70. [Accessed Sep. 25, 2021].