April 2017

Smart Battery Charger

Seth O. Gyebi
Worcester Polytechnic Institute

Repository Citation

Gyebi, S. O. (2017). *Smart Battery Charger*. Retrieved from https://digitalcommons.wpi.edu/mqp-all/2923

Major Qualifying Project

Smart Battery Charger

Students: Seth Gyebi

Advisor: Professor Alexander E. Emanuel

Term: C/D 2017

Submitted to:
Department of Electrical and Computer Engineering

Smart Battery Charger

A Major Qualifying Project

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfilment of the requirements for the
Degree of Bachelor of Science

By
Seth Gyebi

Date:
25 March 2017

ACKNOWLEDGEMENTS

I would like to thank my advisor Professor Alexander E. Emanuel for his continuing help and expertise in developing and completing this project. I would also like to thank all the previous MQP teams who have worked on similar projects for laying the groundwork for my own.

ABSTRACT

The purpose of this project was to design, build and test a 1A smart battery charger that accurately and efficiently charges a 3V, 6V or 12V battery. The smart battery charging system integrated an AC/DC converter, a MOSFET driver circuit, and a DC/DC converter to charge the battery. The concepts of experimental design and simulation were observed.

Table of Contents

TABLE OF FIGURES

1 CHAPTER 1: Introduction

The purpose of this project was to introduce and provide a detailed description and practical analysis of the project design approach to build a smart battery charger. The original design for a smart charger consisted of a number of modules; an AC/DC conversion circuit, a driver circuit and a filter circuit. A full bridge rectifier will be used to convert an AC source (110/220V) to DC. A switch and a fuse were placed in series to prevent damage in the event of a power spike. In addition to regulating the power output to charge the battery, the power source supplies the astable multivibrator to power the driver to regulate the charging voltage.

2 CHAPTER 2: Architectural Description

The figure below describes the basic architecture features of the smart battery charger.

The battery charger is made up of the following functional blocks:

2.1 Project Overview

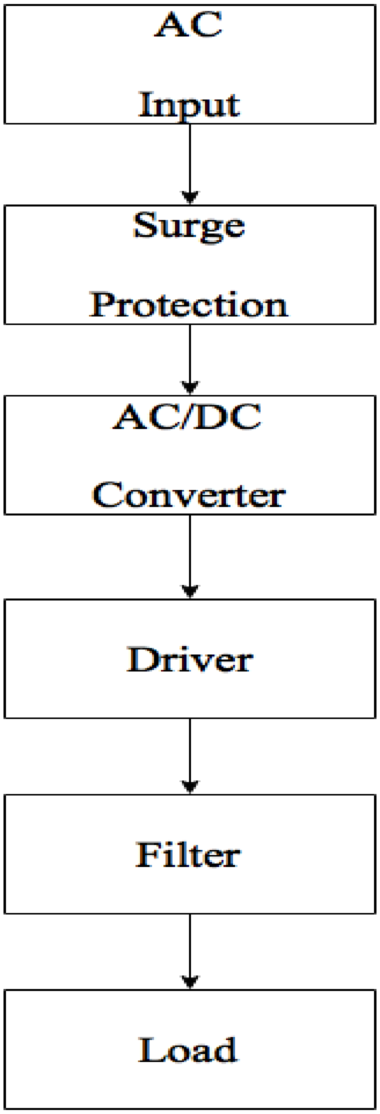


Figure 1: Flow Chart.

2.2 Modular Breakdown

2.2.1 Surge Protection

Surge protection is necessary for our product. A surge protector limits the voltage supplied to an electric device by blocking or shorting to ground any unwanted voltages above a safe threshold [7]. The charger needs to be capable of tolerating fluctuations from the outlet.

Figure 2: Surge protection.

Functionality	**Input**	**Output**	**Status**
Protect against voltage and current spikes on the AC input line.	AC from Outlet (110/240VAC)	AC voltage without spike or transient	Complete

Table 1: Surge Protection Specification

2.2.2 AC /DC Conversion (Rectifier)

The AC/DC rectifier converts 12V (RMS value) AC voltage at the transformer secondary side into a DC voltage. Meanwhile, it must be able to support at least 1A of current for the battery charging.

2.2.3 DC/DC Conversion

The DC/DC converter needs to filter out the rectifier’s DC voltage output ripple and convert it into a clean, constant DC voltage output at the terminal of the battery. The converter must also be able to regulate the DC output to the desired battery charging voltage of either 3V, 6V, or 12V.

3 CHAPTER 3: Module Description and Analysis

The figure below describes the basic architecture features of the smart battery charger. The battery charger is made up of the following functional blocks: an AC Input (circuit protection, transformer), a full bridge rectifier, a diver, and a filter which consists of an inductor and a load.

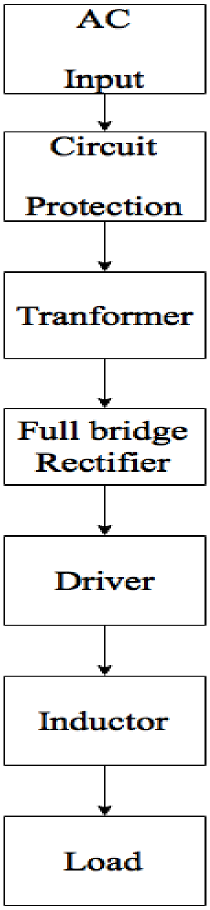


Figure 3: Functional Block Diagram.

The smart battery charger is supplied by $120V_{rms}/240V_{rms}$, $50/60H_z$ AC from the wall. It is protected by a MOV (metal-oxide varistor) switch in the wall outlet that conducts current to ground in cause of a higher voltage [7]. A transformer steps down the voltage to 12V AC_{rms}. Then a full bridge rectifier converts the voltage to a 12V rectified DC waveform. This voltage powers an astable multivibrator which produces a square wave. A comparator (LM311n) controls the duty cycle of the square wave based on the state of the potentiometer [5]. The output of the comparator is boosted by the BJT with the output of the BJT controlling the MOSFET. When the square wave input of the MOSFET switches, then it switches the change of current in the inductor, regulating the output voltage.

3.1 Transformer

In my pursuit for an appropriate transformer, I considered many factors such as input voltage, output voltage, and output current. Since the primary purpose of a transformer is to step down a large AC voltage to a lower AC voltage. I needed to make sure that my transformer would handle both 115 V_{AC} and 230 V_{AC} standards. For the output I needed to make sure that my transformer would be able to handle 24 V_{rms} with a current of 1A. The output requirements of the transformer comes directly from the input requirements of the charging circuit. For my application I used a Jameco #102111-R and the transformer has the following specifications [2]:

Jameco #102111-R	
Specifications	**Values**
Primary voltage	115/230 V_{AC} at 50 – 60Hz
Secondary V_{AC}	24 V at 1A
Power Rating	24 V_A

Table 2: Transformer Specification

3.2 AC/DC Converter

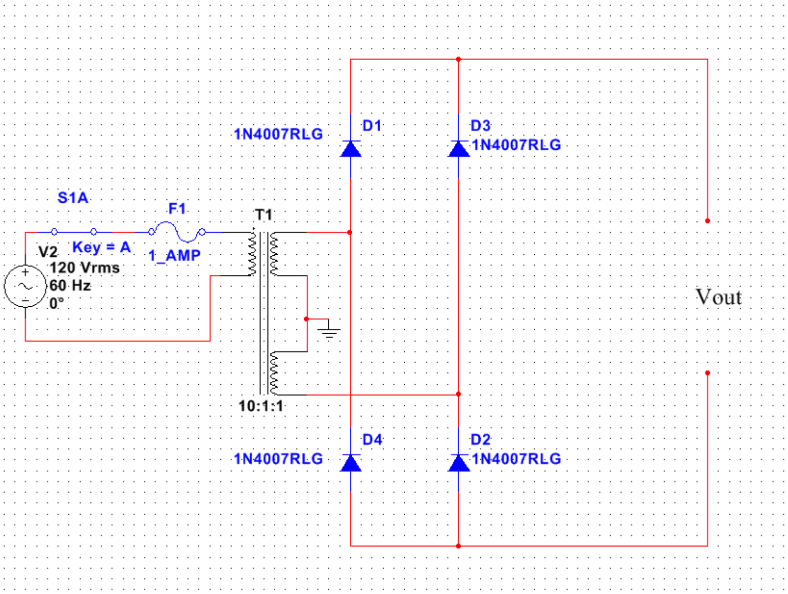


Figure 4: AC/DC Converter Circuit.

The transformer output, the next step in the AC/DC conversion process involves inverting the negative cycles of the AC input. This process requires the use of full wave rectifier Diode Bridge. The rectification takes place by the conduction of couples of diodes. Diodes D1 and D4 are conducting during the positive half-wave of the voltage. Diodes D2 and D3 are conducting during the negative half. In each half-cycle the current flows in both directions in the secondary winding but always in the same direction in the load [1]. There is no DC component in the winding and the core can be smaller than that of a centered-tapped rectifier with the same DC power. I determined that our rectifier would have to be able to handle the peak voltage of 17V along with voltage spikes from a dirty line. The rectifier would able to handle 1A of current. The rectifier that I chose is the 1N4007RLG Bridge rectifier. I found that rectifier in the Digi-key

Online Catalog with the part number 1N4007RLGOSTR-ND [8]. The Specifications below from the online catalog.

Specifications	**Values**
Voltage-Rated	1000V
Current Rating	1A
Package/Case	D0-41

Table 3: Rectifier Specification

3.3 DC/DC Converter

DC/DC converter regulates the output voltage. The converter consists of an astable multivibrator, a comparator, a BJT, a MOSFET and an Inductor filter.

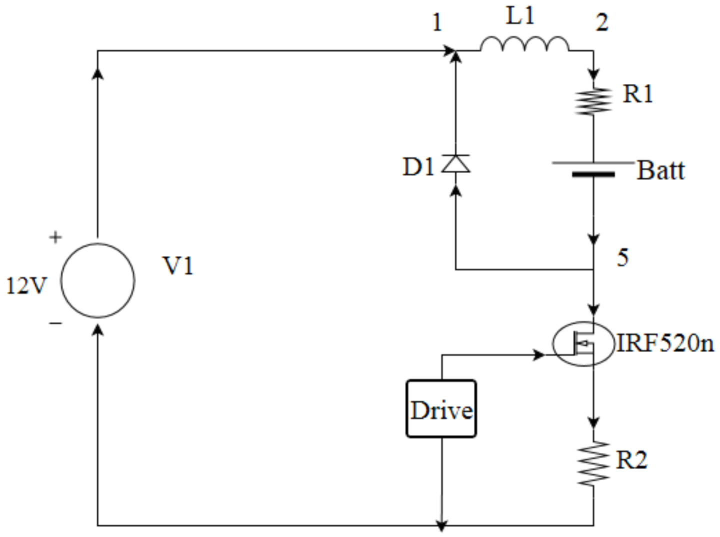


Figure 5: DC/DC Converter Circuit.

For the voltage regulator to be able to handle these higher voltages, I will be using a resistor, a driver, a diode (1N4007RLG), a BJT, Inductor filter and power MOSFET, which essentially acts as a high power voltage divider.

3.3.1 Astable Multivibrator using LM741 OP-AMP

An astable multivibrator is used to generate a triangular wave input to the comparator to create a pulse-width modulation (PWM) signal. The multivibrator functions through a capacitor, connected to inverting input of the LM741 OP-AMP, charging and discharging. As the capacitor charges, the output voltage of the OP-AMP oscillators between the positive and negative rails. As the output switches, the capacitor continues discharging and charging continuing to generate the square wave [6].

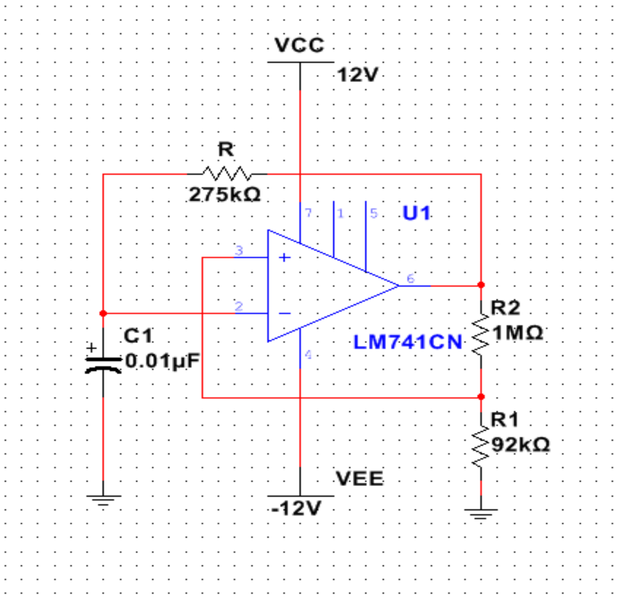


Figure 6: Timer astable circuit.

The measured values of the component use in this circuit is:

R = 275 kΩ

R1 = 92 kΩ

R2 = 1MΩ

C1 = 0.01 uF

$$f = \frac{1}{2RC}$$

Equation 1: Frequency of the astable multivibrator [9].

Using the values of R = 275 kΩ and C1 = 0.01uF I got 181.1 Hz.

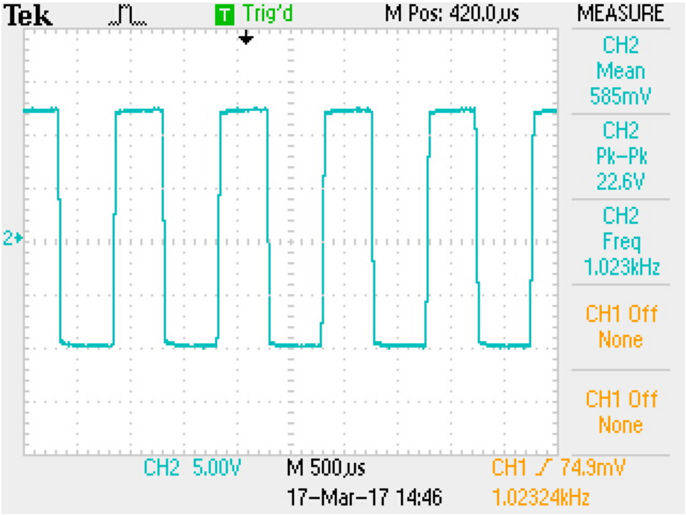


Figure 7: Timer astable multivibrator output square wave.

The figure 7 above is the output square wave of the astable multivibrator. The square wave is needed to be convert to a triangular wave in order to be compare with the control voltage. Oscillator can also generate a wave similar to a triangular wave.

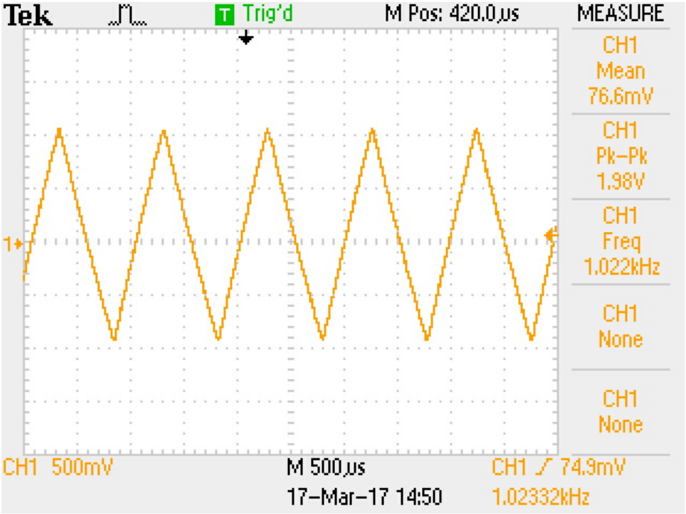


Figure 8: Timer astable multivibrator capacitor voltage.

The triangular wave produced by the capacitor could also be used to compare with the control voltage, but before it can be use it need to be amplify and adjust the offset.

3.3.2 Comparator

The purpose of the comparator in figure (10) is to output a square wave of amplitude of 10V and duty cycle whose value is based on the value of $V_{control}$.

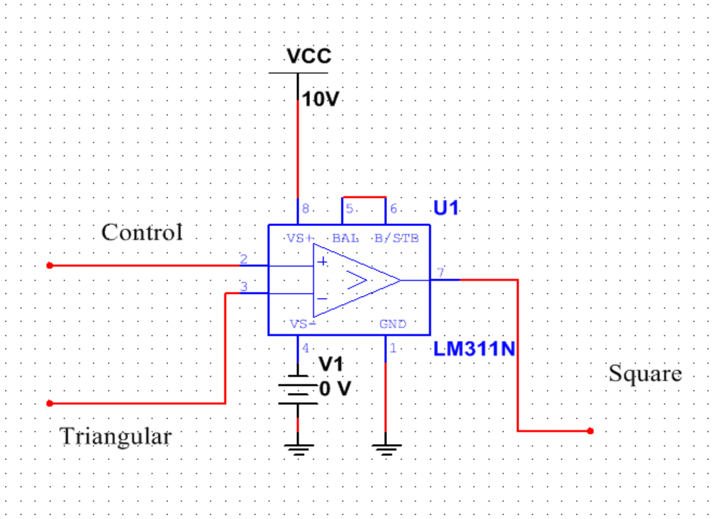


Figure 9: Comparator.

The output of the comparator, $V_{Square,}$ supplies the switch transistors in the DC/DC converter with the square wave required for the switching operation. The non-inverting input is a fixed amplitude and frequency triangular wave, $V_{triangular}$. The inverting input is a DC voltage, $V_{control}$. The duty cycle increases when $V_{control}$ increases and decreases when $V_{control}$ decreases. When $V_{tri} < V_{control}$, V_{Square} is High (10 volts) and when $V_{tri} > V_{control}$, V_{Square} is Low (0 volts) [5].

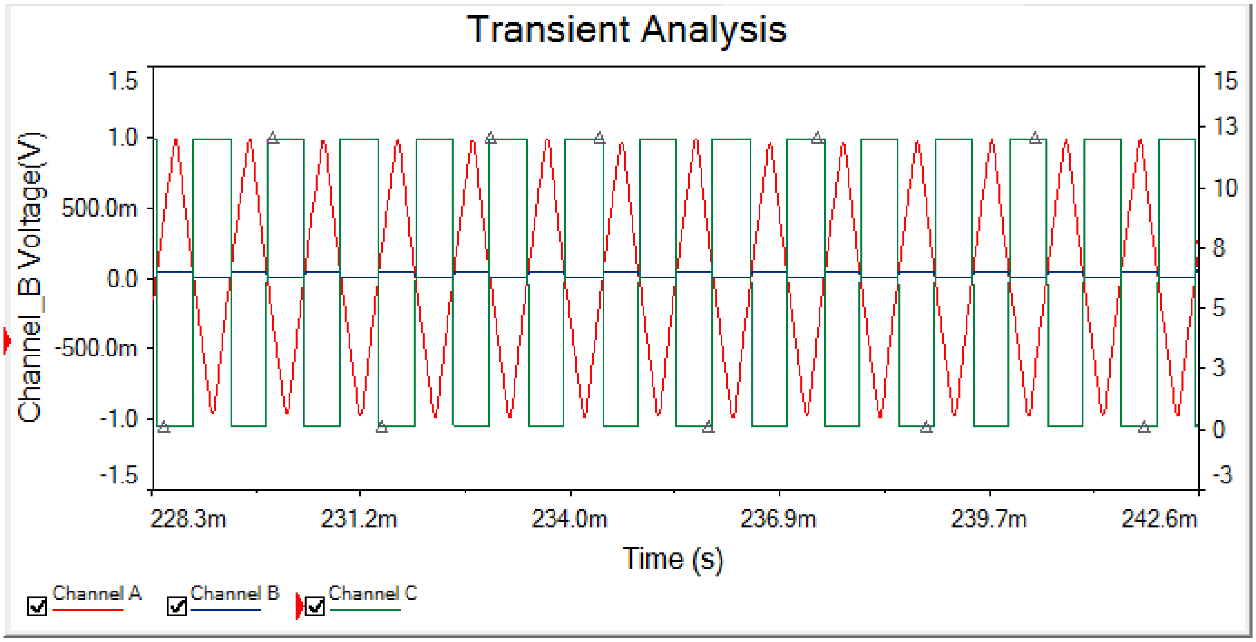


Figure 10: Comparator input and output waveform. Red is input, blue is control voltage and green is output.

A triangular wave was compared with a control voltage to produce a square wave. This square wave is going to the gate of the MOSFET of the DC/DC converter. Depending on if the control voltage increases or decreases, the square duty cycle will change according to the change of the control voltage.

3.3.3 BJT

The PWM from the comparator is the input to BJT which allows the MOSFET to switch. The BJT allows the MOSFET to switch faster by conducting a greater amount of current than that could be supplied by the output of the comparator. When the BJT is ON, the gate of the MOSFET is charged and the MOSFET turns ON [1].

3.3.4 MOSFET

An IRF520 N-Channel power MOSFET was used to control the switch of the battery charger. The gate of the MOSFET is being driven by a pulse – width modulated (PWM) signal to minimize power losses in the circuit. The duty cycle of the control signal determines the average DC voltage applied to the battery charger, thus controlling the switches. The diode in the circuit is a "feel-wheeling diode" to provide a path for the induced charger current to flow, when the MOSFET turn OFF. Without this diode, a high voltage spike would occur across the MOSFET during turn-off and would damage or MOSFET [1].

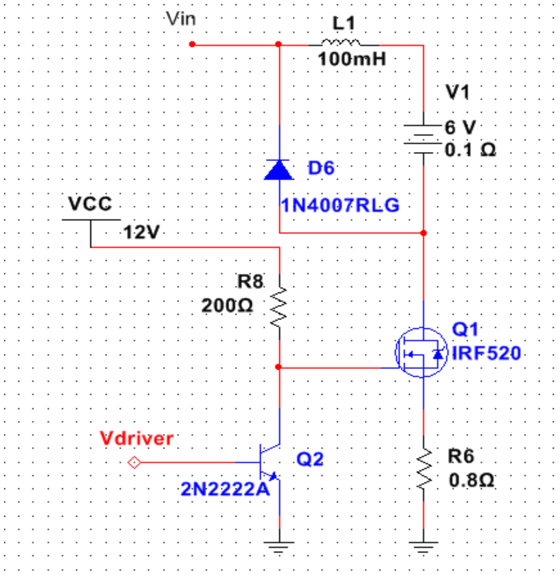


Figure 11: MOSFET and BJT

3.3.5 Filter Inductor

The current in the inductor cannot change instantaneously. This property helps the inductor to filter out the current ripple and obtain a more constant charging current flow into the battery. In this project, we use part of a transformer secondary winding as the filter inductor, measured value of 100 mH. This results an average charging current that is 1A.

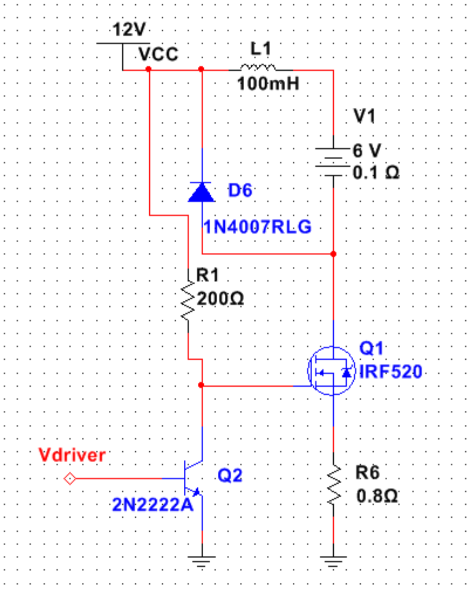


Figure 12: Filter inductor output

The inductor needs to have a minimum value to result a continuous current flow. Given the switching frequency of the driver circuit as 1000Hz, we can use the following equation to calculate the minimum inductance value,

$$L_{min} = \frac{(1-D)R}{2f}$$

Where R is the equivalent load resistance value. In this study, we have the load modeled as the battery voltage source in series with its internal resistance. It is necessary to account that in the minimum inductor value calculation. Nevertheless, the 100mH inductor will ensure the continuous current flow under all the possible operating conditions, both in theory as well as in the actual tests [1].

4. CHAPTER 4: Module Simulation

The simulation of the AC/DC conversion module consisted of a modeled AC input after the 10:1 transformer, a full bridge rectifier, Astable multivibrator (LM741cn and comparator LM311n), a BJT, a MOSFET, a filter inductor and a voltage source and a series resistor. The reason why I went with a 120V AC input, was to model the 120V AC wall source the model for the AC input consisted of 12V_{rms} at 60Hz, which represent the output of the transformer. I tested for different known values for the inductor to see how they would affect the output. The load current that I used in the model was determined to be 1A because that is the maximum current that the charging circuit will draw due to the internal current limiting of the load.

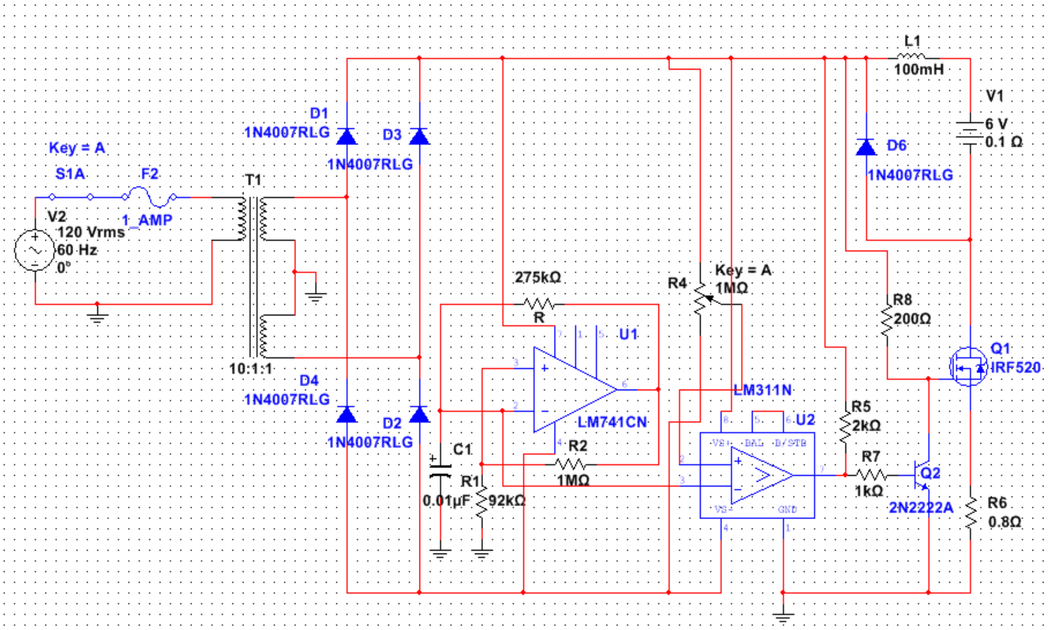


Figure 13: Module simulations circuit

4.1 Multisim Result

I modeled the circuit in Multisim and performed the simulation to confirm the circuit behavior. The rectifier simulation produced a positive polarity DC waveform of 15V. This was what I expected but the voltage was supposed to be 12V. The output waveform astable oscillator and of the comparator were measured. The oscillator produced a triangular wave of about 0.9V peak-to-peak and the comparator produced a square wave output of 5V. Both waves had frequencies of slightly less than 200Hz.

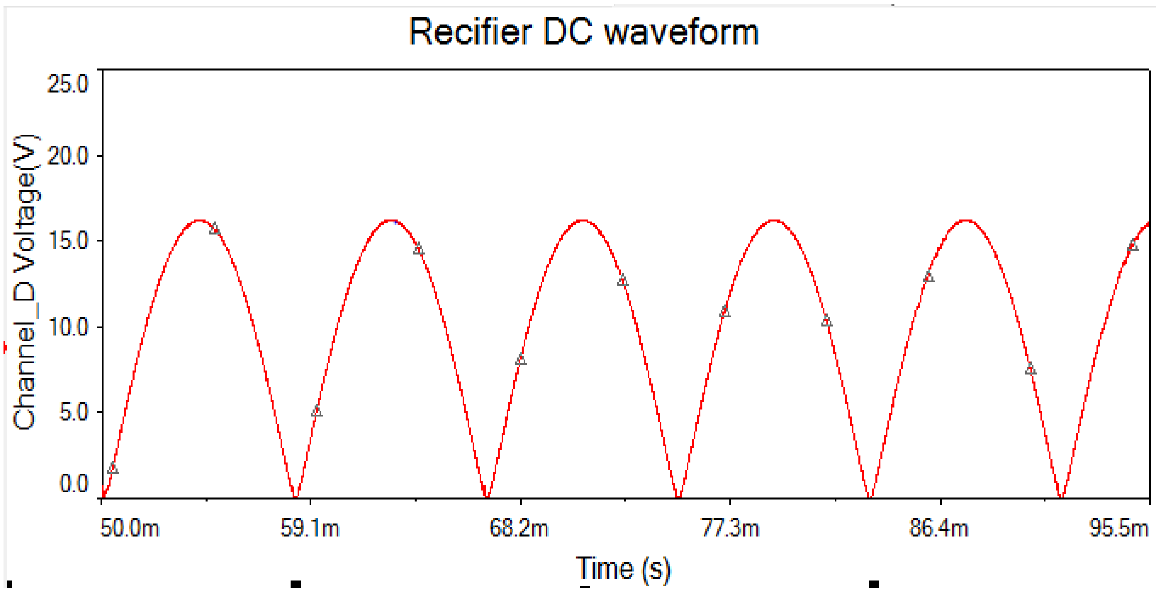


Figure 14: Rectifier DC waveform

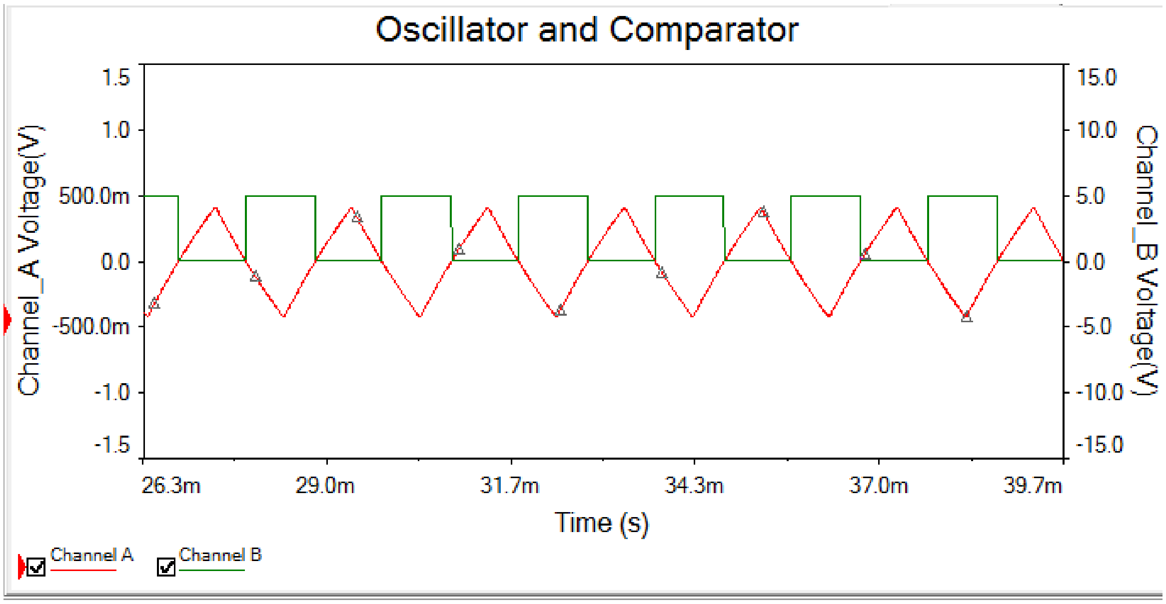


Figure 15: Oscillator and Comparator

4.2 PSpice Simulation

I modeled the circuit in Pspice and performed the simulation to confirm the circuit behavior.in the Pspice code I used the following nodes to measure from as shown in figure 16. The Pspice code can be found in the Appendix A.

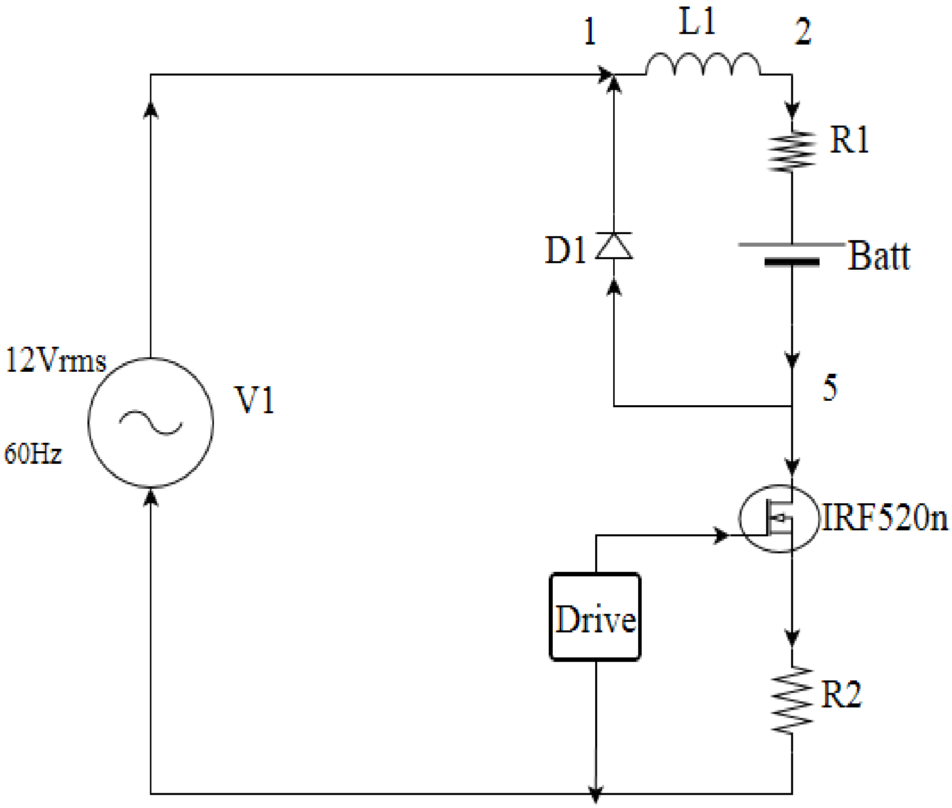


Figure 16: Pspice simulation circuit

4.3 Pspice Result

In the Pspice simulations, I measured the current through the inductor between nodes 1 and node 2. The result was a triangular wave of 31mA and frequency of 1000Hz.

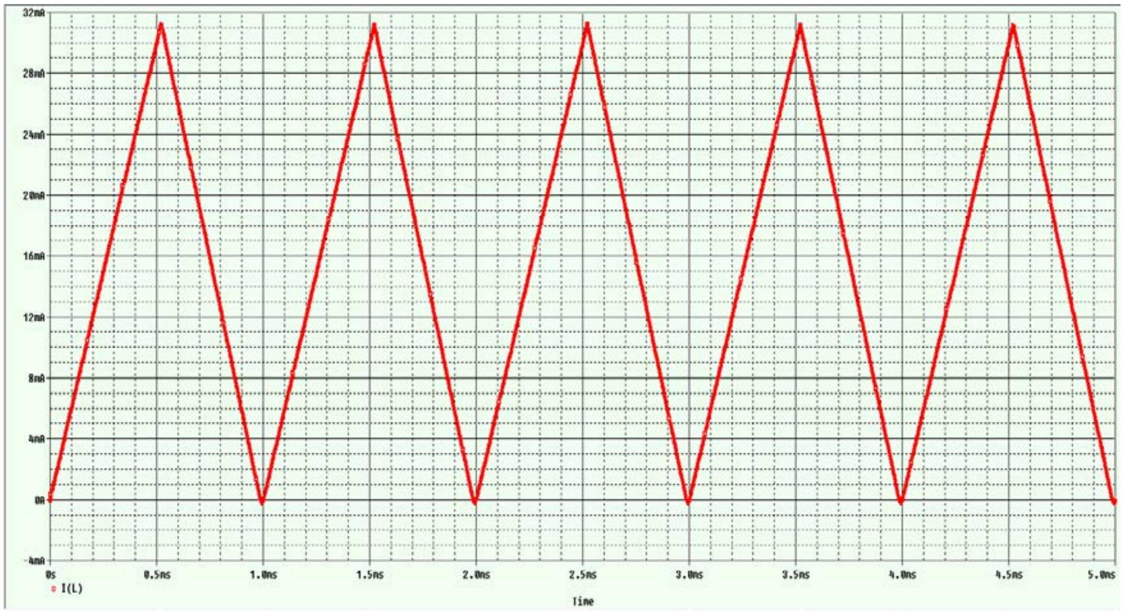


Figure 17: Simulated waveform for the current inductor.

The voltage across the inductor was a square waveform from -6.8V to +6V and a frequency of a 1000Hz.

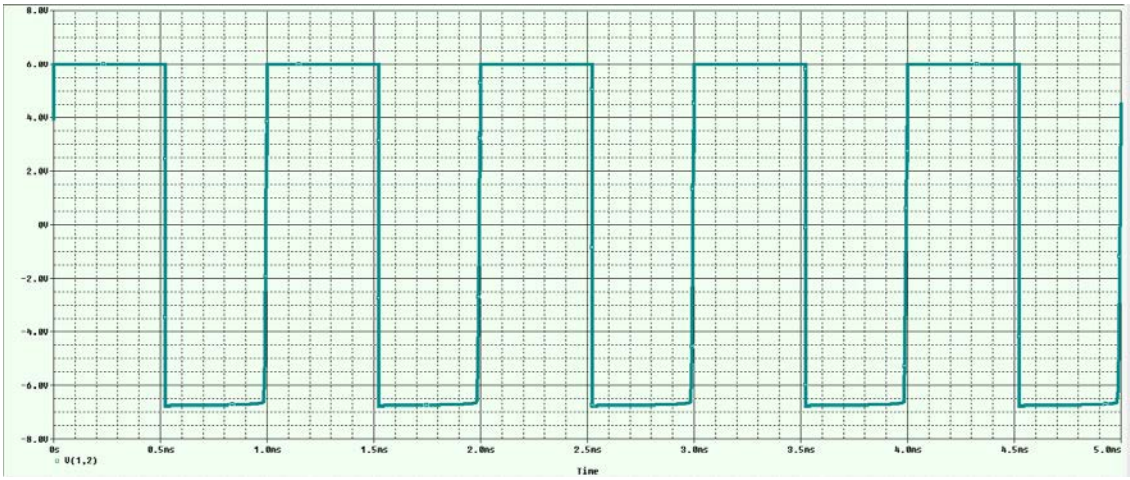


Figure 18: Simulated waveform for voltage of the inductor

The voltage across the load and inductor was a square waveform from -0.8V to +12V and a frequency of a 1000Hz

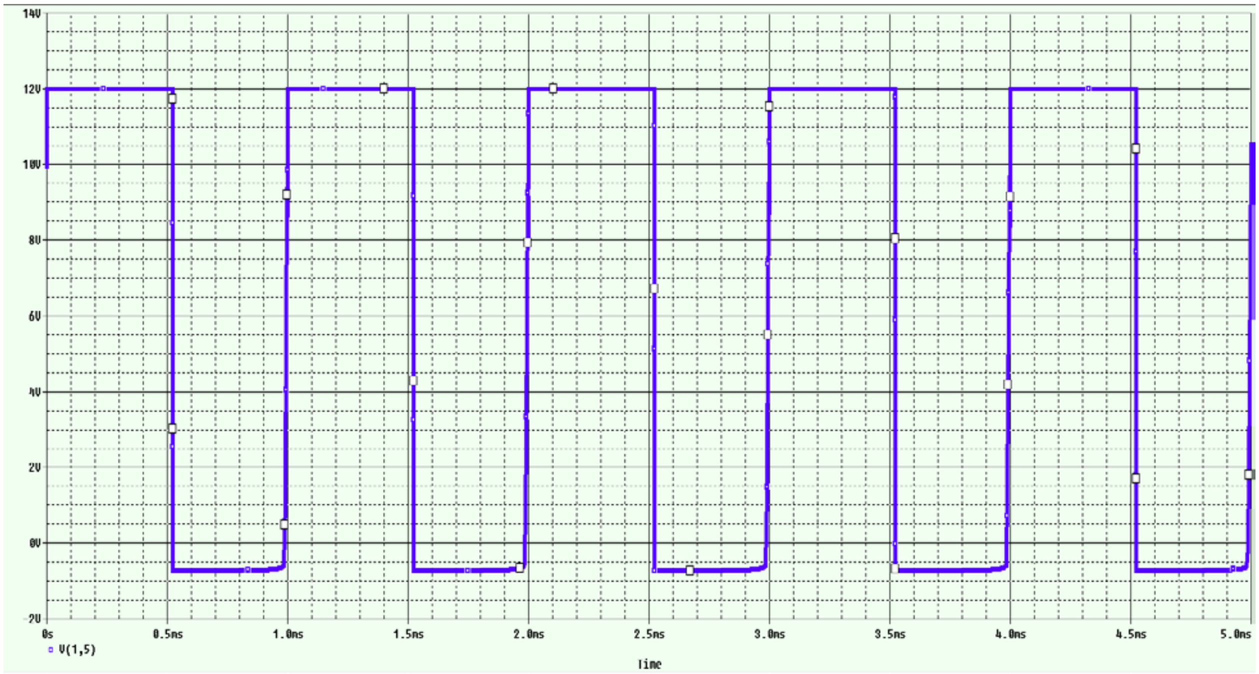


Figure 19: Simulated waveform for the voltage of the diode, inductor and the load.

The voltage across the load was about 6V with a triangular volt ripple 0.003V and a frequency of a 1000Hz.

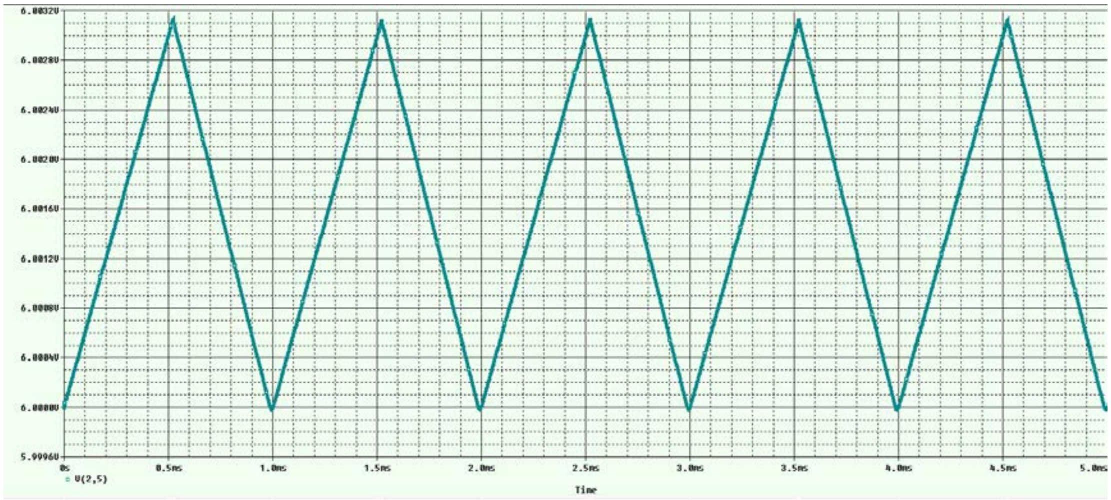


Figure 20: Simulated waveform for the voltage of the load

The voltage across the MOSFET was a square waveform from 0V to 12.7V and a frequency of a 1000Hz.

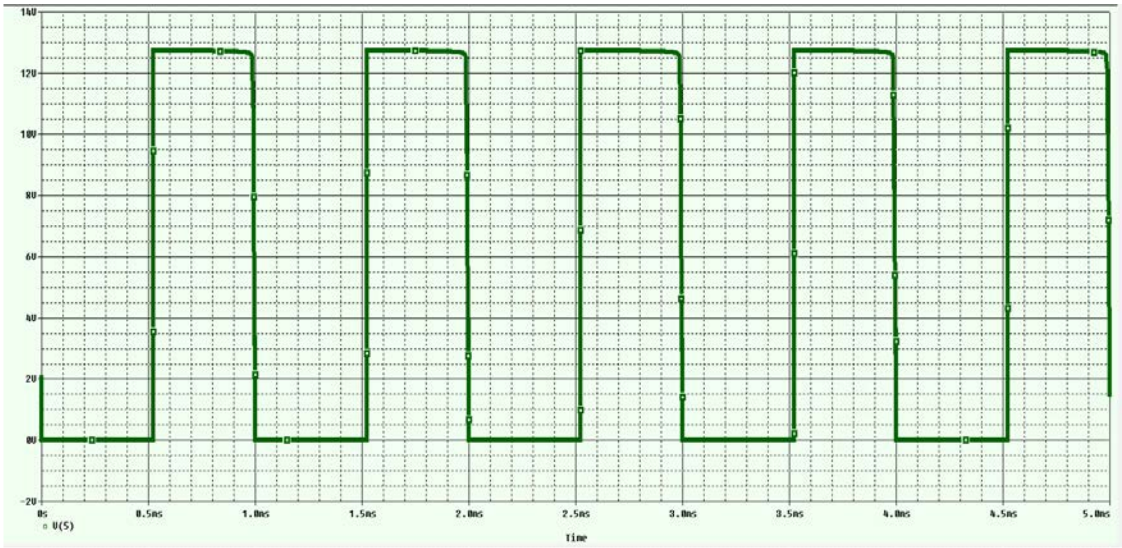


Figure 21: Simulated waveform for the voltage of the MOSFET.

The voltage across the driver was a square waveform from 0V to 10V and a frequency of a 1000Hz.

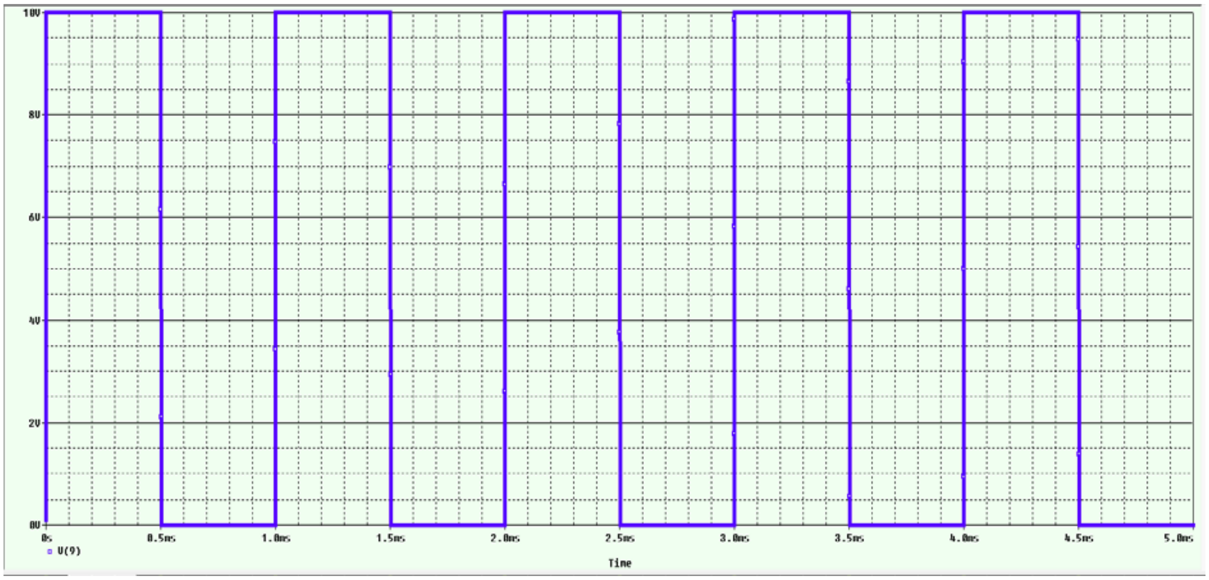


Figure 22: Simulated waveform for the voltage of the driver

The current between the inductor and a diode was a waveform from 0A to 30mA and a frequency of a 1000Hz.

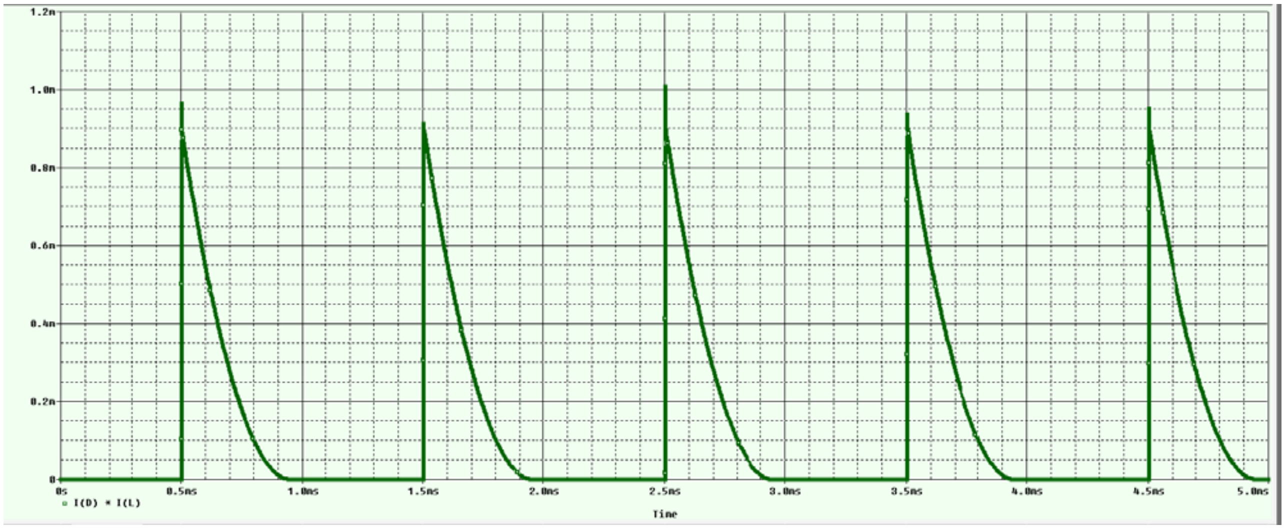


Figure 23: Simulated waveform current between diode

5 CHAPTER 5: System Testing

The complete system will involve individual testing of each module for functionality so that it will work with the rest of the modules. The modules that will need to be tested will be the AC/DC conversion module, the driver circuit, inductor output module and battery charging verification.

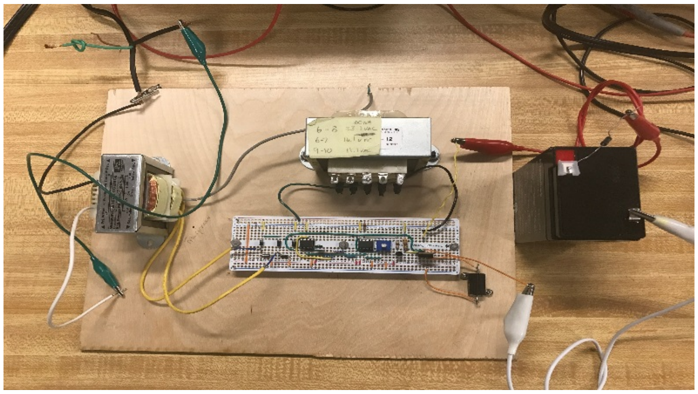


Figure 24: Smart battery charger circuit.

5.1 AC/DC Module Testing

This module will need to be able to produce an acceptable DC output from both 115V and 230V (AC) inputs. To test this module, I needed to connect the oscilloscope to the output of the full bridge rectifier. The output of the rectifier is shown on Channel 1 of the figure (26) below. The two different polarity legs of the rectifier are shown on Channel 2 and Channel 3. The rectifier performed I expected.

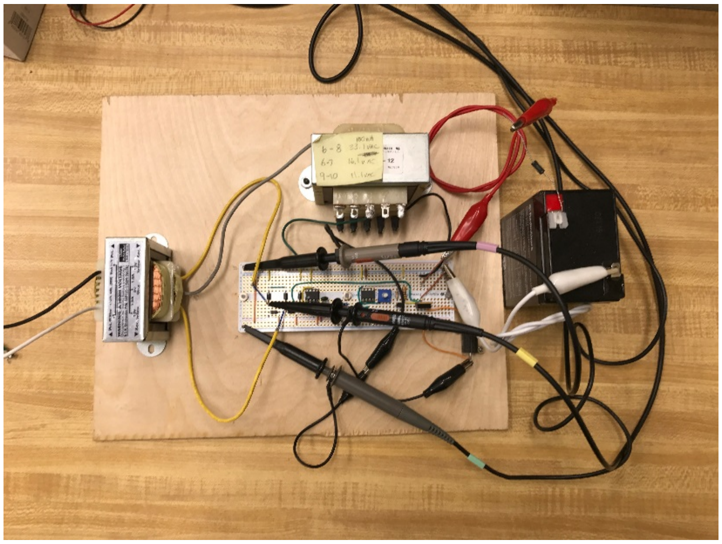


Figure 25: AC/DC Module testing.

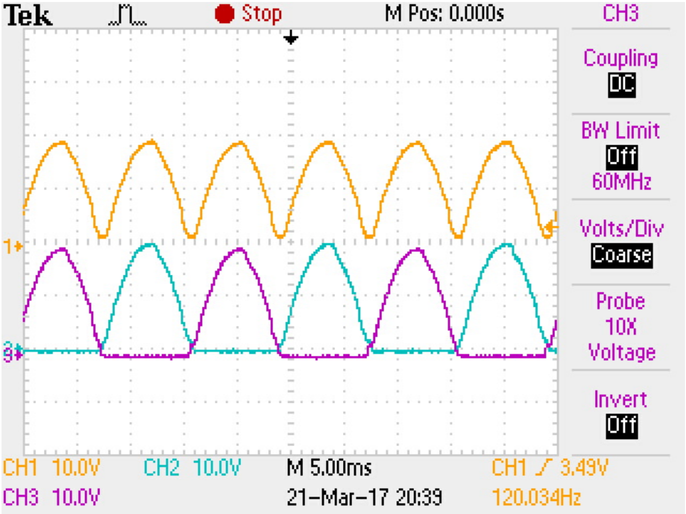


Figure 26 : Measured waveform for the output rectifier and the polarity legs of the rectifier.

5.2 Driver Circuit Testing

The output of the oscillator and comparator were measured on the oscilloscope. The oscillator was shown the output of triangular waveform bounded by a sinusoidal envelope. The highest value of the triangular waveform seemed to be limited by the rail voltage of the op-amp.

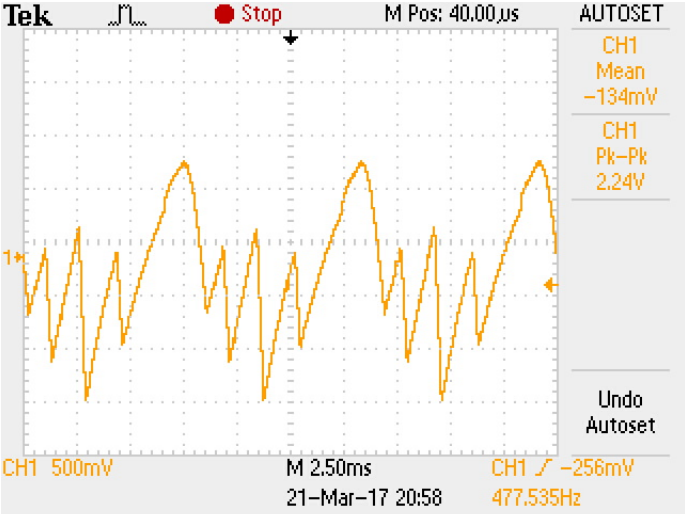


Figure 27: Measured oscillator output.

The output of the comparator was a PWM square wave of approximately 0.8V.

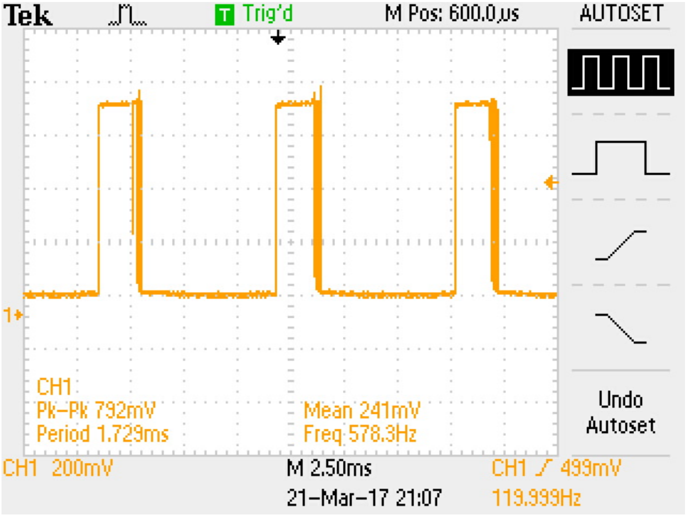


Figure 28: Measured comparator output.

5.3 Inductor Output Testing

The output of a full bridge converter leads to a buck converter, which consists of an inductor and a diode (1N4007RLG) feeding the load. A convenient aspect of this bridge driven buck topology is that the output stage ripple actually occurs at twice the switching frequency, making it easier to filter [1]. However, the smart charger will need to be able to supply a voltage at 14.8V DC or above, depending on the battery level. Once the battery is fully charged, 12.8 V DC is applied across its terminals.

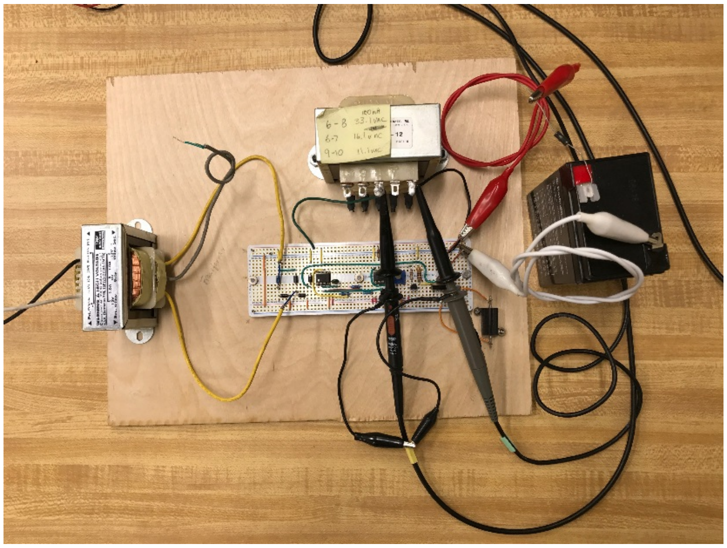


Figure 29: Inductor output testing.

The inductor voltage was measured with the oscilloscope and was shown to produce a voltage similar to the rectified DC waveform. Because the buck converter part of the circuit was not functioning properly, the DC waveform was not properly regulated to a constant DC output.

5.4 Final battery charging verification

When tested the battery charger circuit did not work as expected. The output to the battery appeared to charge at only about 20mA and the output voltage was shown to be similar to the rectifier DC waveform. To determine the cause of this problem, the outputs of the astable multivibrator and comparator were measured, and no PWM signal was being generated. This was likely due to how the op-amp and comparators were being powered. The rail voltages were supplied by the rectified DC instead of from a constant DC source. If the rails were powered by DC, the driver PWM signal may have been generated properly.

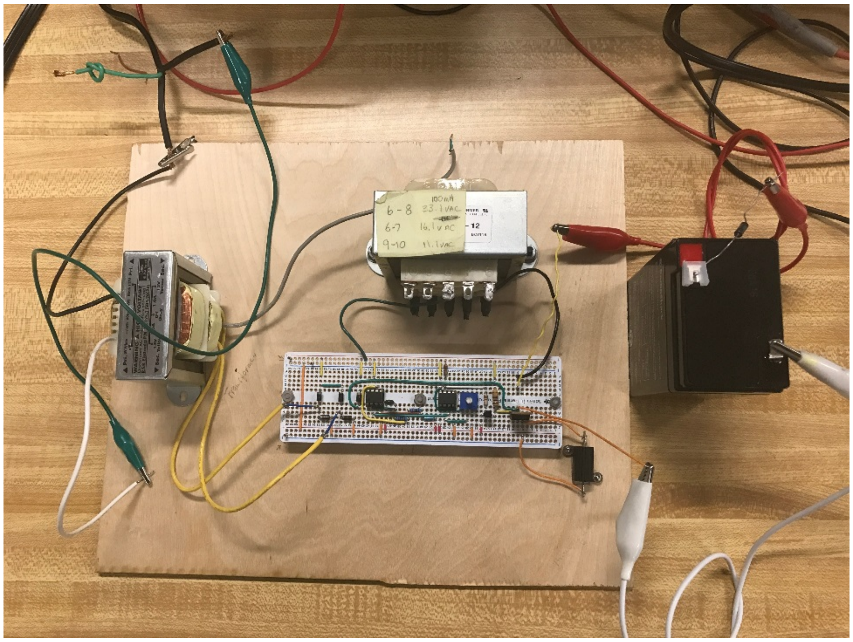


Figure 30: Battery charger verification

6 Conclusion

My project was a Smart battery charger to charge a sealed lead-acid battery. My goal was to design, simulate, and build a Smart battery charger. The circuit was simulated in Pspice to verify design before construction. A prototype circuit board was built and all components soldered by hand, including a high frequency transformer and inductor. Testing, revision, and analysis of the completed circuit board was performed. The result was successful.

7 References

[1] Hart DW. *Power electronics*. 1st ed. New York, NY: McGraw, Hill; 2011:439.

[2] Power transformer 24vct@1A 115/230VAC wire leads. http://www.jameco.com Web site. http://www.jameco.com/z/102111-R-Power-Transformer-24vct-1A-115-230VAC-Wire-Leads_102112.html. Accessed Mar 24, 2017.

[3] Gleyzer V, Masullo S, Mulla J. Design and integration. *WORCESTER POLYTECHNIC INSTITUTE*. 2003:1-20.

[4] Apollonio B, king C, Murray S. Unity power factor universal batterry charger. *WORCESTER POLYTECTNIC INSTITUTE*. 2006:1-112.

[5] Le NT, Sbat A. Solar battery charger. *WORCESTER POLTECHNIC INSTITUTE*. :10-39.

[6] Brahma Chary PS. Operational amplifier as astable multivibrator. GOVERNMENT POLYTECHNIC KOTHAGUDEM Web site. http://kothagudemgovtpoly.nic.in/StudentsCorner/StudentsCorner117.pdf. Accessed Mar 17, 2017.

[7] Surge protector. wikipedia.org Web site. https://en.wikipedia.org/wiki/Surge_protector. Updated 2017. Accessed 12 March, 2017.

[8] ON semiconductor 1N4007RLG. Digikey, Web site. https://www.digikey.com/product-detail/en/on-semiconductor/1N4007RLG/1N4007RLGOSTR-ND/918021. Accessed Mar 24, 2017.

[9] Op-amp multivibrator. electronics-tutorials.ws Web site. http://www.electronics-tutorials.ws/opamp/op-amp-multivibrator.html. Accessed Mar 24, 2017.

Appendix A

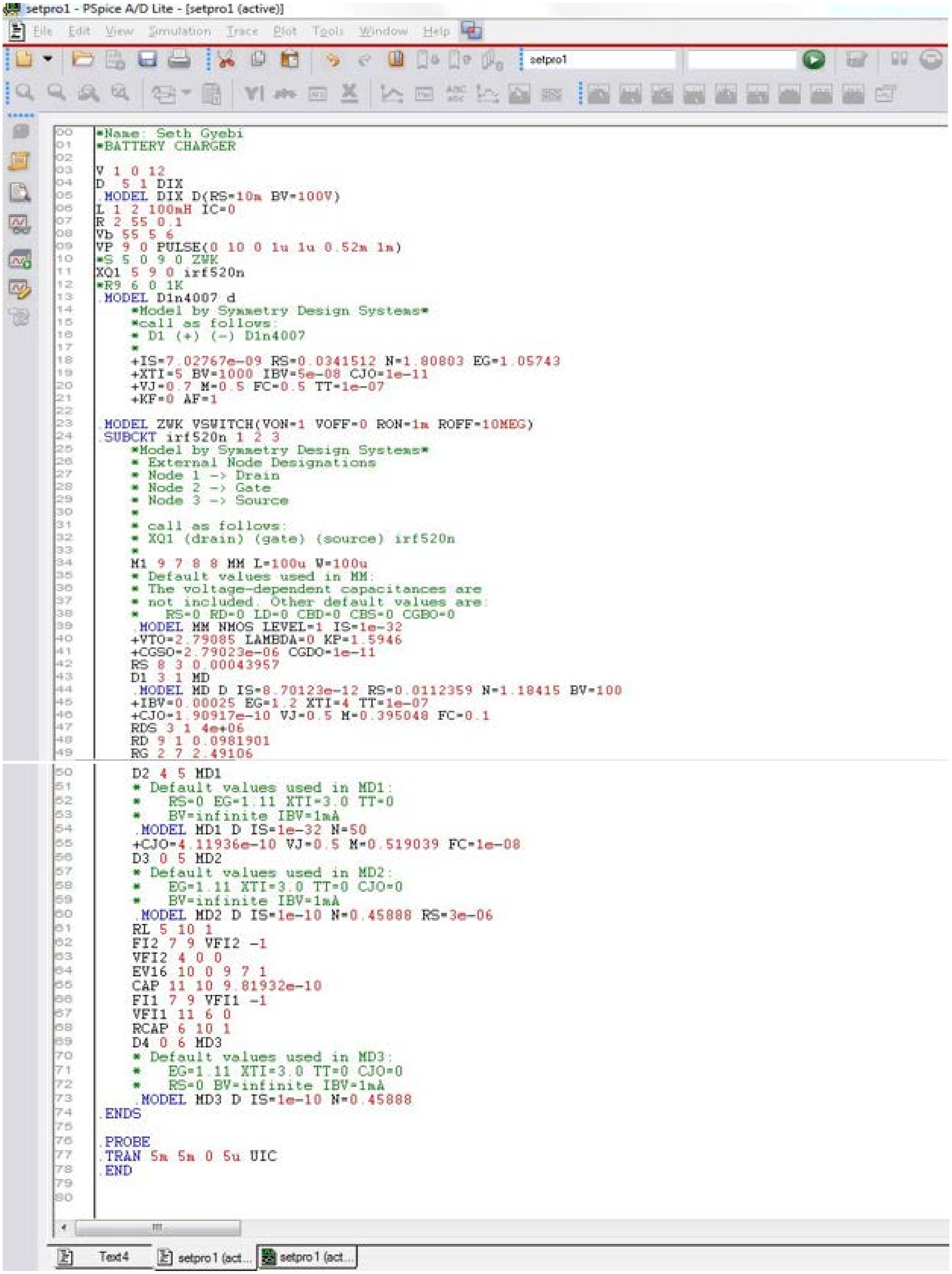
```
*Name: Seth Gyebi
*BATTERY CHARGER


V 1 0 12
D 5 1 DIX
.MODEL DIX D (RS=10m BV=100V)
L 1 2 100mH IC=0
R 2 55 0.1
Vb 55 5 6
VP 9 0 PULSE (0 10 0 1u 1u 0.52m 1m)
*S 5 0 9 0 ZWK
XQ1 5 9 0 irf520n
*R9 6 0 1K
.MODEL D1n4007 d
        *Model by Symmetry Design Systems*
        *call as follows:
        * D1 (+) (-) D1n4007
```

```
	*
	+IS=7.02767e-09 RS=0.0341512 N=1.80803 EG=1.05743
	+XTI=5 BV=1000 IBV=5e-08 CJO=1e-11
	+VJ=0.7 M=0.5 FC=0.5 TT=1e-07
	+KF=0 AF=1

.MODEL ZWK VSWITCH (VON=1 VOFF=0 RON=1m ROFF=10MEG)
.SUBCKT irf520n 1 2 3
	*Model by Symmetry Design Systems*
	* External Node Designations
	* Node 1 -> Drain
	* Node 2 -> Gate
	* Node 3 -> Source
	*
	* call as follows:
	* XQ1 (drain) (gate) (source) irf520n
	*
	M1 9 7 8 8 MM L=100u W=100u
```

```
* Default values used in MM:
* The voltage-dependent capacitances are
* not included. Other default values are:
*   RS=0 RD=0 LD=0 CBD=0 CBS=0 CGBO=0
.MODEL MM NMOS LEVEL=1 IS=1e-32
+VTO=2.79085 LAMBDA=0 KP=1.5946
+CGSO=2.79023e-06 CGDO=1e-11
RS 8 3 0.00043957
D1 3 1 MD
.MODEL MD D IS=8.70123e-12 RS=0.0112359 N=1.18415 BV=100
+IBV=0.00025 EG=1.2 XTI=4 TT=1e-07
+CJO=1.90917e-10 VJ=0.5 M=0.395048 FC=0.1
RDS 3 1 4e+06
RD 9 1 0.0981901
RG 2 7 2.49106
D2 4 5 MD1
* Default values used in MD1:
*   RS=0 EG=1.11 XTI=3.0 TT=0
```

```
*   BV=infinite IBV=1mA
.MODEL MD1 D IS=1e-32 N=50
+CJO=4.11936e-10 VJ=0.5 M=0.519039 FC=1e-08
D3 0 5 MD2
* Default values used in MD2:
*   EG=1.11 XTI=3.0 TT=0 CJO=0
*   BV=infinite IBV=1mA
.MODEL MD2 D IS=1e-10 N=0.45888 RS=3e-06
RL 5 10 1
FI2 7 9 VFI2 -1
VFI2 4 0 0
EV16 10 0 9 7 1
CAP 11 10 9.81932e-10
FI1 7 9 VFI1 -1
VFI1 11 6 0
RCAP 6 10 1
D4 0 6 MD3
* Default values used in MD3:
```

```
    *   EG=1.11 XTI=3.0 TT=0 CJO=0
    *   RS=0 BV=infinite IBV=1mA
    .MODEL MD3 D IS=1e-10 N=0.45888
.ENDS

.PROBE
.TRAN 5m 5m 0 5u UIC
.END
```



```
*Name: Seth Gyebi
*BATTERY CHARGER

V 1 0 12
D  5 1 DIX
.MODEL DIX D(RS=10m BV=100V)
L 1 2 100mH IC=0
R 2 55 0.1
Vb 55 5 6
VP 9 0 PULSE(0 10 0 1u 1u 0.52m 1m)
*S 5 0 9 0 ZWK
XQ1 5 9 0 irf520n
*R9 6 0 1K
.MODEL D1n4007 d
    *Model by Symmetry Design Systems*
    *call as follows:
    * D1 (+) (-) D1n4007
    *
    +IS=7.02767e-09 RS=0.0341512 N=1.80803 EG=1.05743
    +XTI=5 BV=1000 IBV=5e-08 CJO=1e-11
    +VJ=0.7 M=0.5 FC=0.5 TT=1e-07
    +KF=0 AF=1

.MODEL ZWK VSWITCH(VON=1 VOFF=0 RON=1m ROFF=10MEG)
.SUBCKT irf520n 1 2 3
    *Model by Symmetry Design Systems*
    * External Node Designations
    * Node 1 -> Drain
    * Node 2 -> Gate
    * Node 3 -> Source
    *
    * call as follows:
    * XQ1 (drain) (gate) (source) irf520n
    *
    M1 9 7 8 8 MM L=100u W=100u
    * Default values used in MM:
    * The voltage-dependent capacitances are
    * not included. Other default values are:
    *   RS=0 RD=0 LD=0 CBD=0 CBS=0 CGBO=0
    .MODEL MM NMOS LEVEL=1 IS=1e-32
    +VTO=2.79085 LAMBDA=0 KP=1.5946
    +CGSO=2.79023e-06 CGDO=1e-11
    RS 8 3 0.00043957
    D1 3 1 MD
    .MODEL MD D IS=8.70123e-12 RS=0.0112359 N=1.18415 BV=100
    +IBV=0.00025 EG=1.2 XTI=4 TT=1e-07
    +CJO=1.90917e-10 VJ=0.5 M=0.395048 FC=0.1
    RDS 3 1 4e+06
    RD 9 1 0.0981901
    RG 2 7 2.49106
    D2 4 5 MD1
    * Default values used in MD1:
    *   RS=0 EG=1.11 XTI=3.0 TT=0
    *   BV=infinite IBV=1mA
    .MODEL MD1 D IS=1e-32 N=50
    +CJO=4.11936e-10 VJ=0.5 M=0.519039 FC=1e-08
    D3 0 5 MD2
    * Default values used in MD2:
    *   EG=1.11 XTI=3.0 TT=0 CJO=0
    *   BV=infinite IBV=1mA
    .MODEL MD2 D IS=1e-10 N=0.45888 RS=3e-06
    RL 5 10 1
    FI2 7 9 VFI2 -1
    VFI2 4 0 0
    EV16 10 0 9 7 1
    CAP 11 10 9.81932e-10
    FI1 7 9 VFI1 -1
    VFI1 11 6 0
    RCAP 6 10 1
    D4 0 6 MD3
    * Default values used in MD3:
    *   EG=1.11 XTI=3.0 TT=0 CJO=0
    *   RS=0 BV=infinite IBV=1mA
    .MODEL MD3 D IS=1e-10 N=0.45888
.ENDS

.PROBE
.TRAN 5m 5m 0 5u UIC
.END
```