St. Cloud State University

Department of Electrical and Computer Engineering

Final Project Report

Design a DC-DC IC Buck Converter Power Supply from an input transformer 120/48 V_{RMS}

ECE 411 Advanced Analog Electronics– Prof. Timothy Vogt

December 17, 2021

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Background

This final project is to design a DC-DC converter power supply using a buck converter with an output of 5 Watts. The design starts with a transformer a VAC input and output voltage of 115/48 V RMS and a full-wave rectifier circuit to rectify the voltage and a power factor correction circuit (Valley Fill Circuit is used in this case) to correct the power supply for 75% and higher. The output of the power factor correction circuit works as an input to the DC-DC buck converter, which outputs 5 watts.

Objectives

To learn how to design, simulate, and build an AC-to-DC power supply, with filtering to minimize ripple and improve power factor. The power supply will output a DC voltage that results in 5 watts at a maximum current of 1 amp.

Other important objectives will be learned when designing the system:

i) Selecting and sizing the right components for diodes, resistors, and capacitors.

ii) Purchasing the material and knowing what are the right components that work with the design.

iii) Soldering the component on the PCB board.

iv) Understanding datasheets.

v) Taking measurements and finding out the errors.

System Requirements and Design Specifications

Basic requirements:

The required devices in this system are as follow:

1. Quick Pack small power transformer VAC 115/48 V_{RMS} at 60Hz (Given).
2. Diodes for the rectifier circuit.
3. Resisters, diode, and capacitors for the power factor correction circuit.
4. Wires.
5. Breadboard.
6. IC Regulator Buck converter with external components like Schottky diode, capacitors, inductors, and resisters.
7. PCB board.
8. Soldering equipment (Given).

Design specifications:

The design specifications are based on the results of 5 watts created from 5V or more with 1 A. Also, the power factor must be more than 0.7. The overall design contains AC source, AC line filter, rectifier and power factor correction, and DC-DC Converter with control. See figure (1) below for a sample schematic diagram.

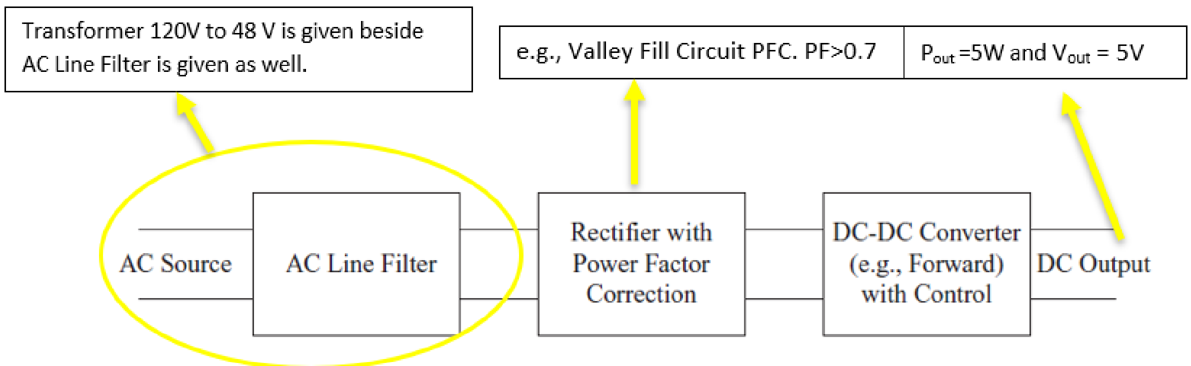


Figure (1) A complete power supply when the source is the ac power system.

Design, Calculation, and Simulation

AC Input Source (Transformer 120/48 or 115/48):

The design was approached by starting with building the transformer and full-wave rectifier circuit using LTSpice. Building transformer in LTSpice using the calculation below

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P}$$

N_1 is N_P (primary) and N_2 is N_S (secondary)

V_1 is V_P (primary) and V_2 is V_S (secondary)

V_1 = 120V, V_2 = 48V, and the ratio assumed to be 1 to 1 (1:1)

$$\frac{120}{48} = \frac{N_1}{1} \longrightarrow \text{therefore } N_1 = 2.5$$

The inductor for the primary is 2.5mH and for the secondary is 1mH and based on the transformer given, it was found that the output is not exactly 48V, it was found to be about 57V. However, the modification of the primary inductor increased to 2.6mH to get the same output as the ideal transformer. In this case, the calculation value will be kept and used in the simulation. See figure (1) for the LTSpice transformer circuit and figure (2) for the output voltage in RMS.

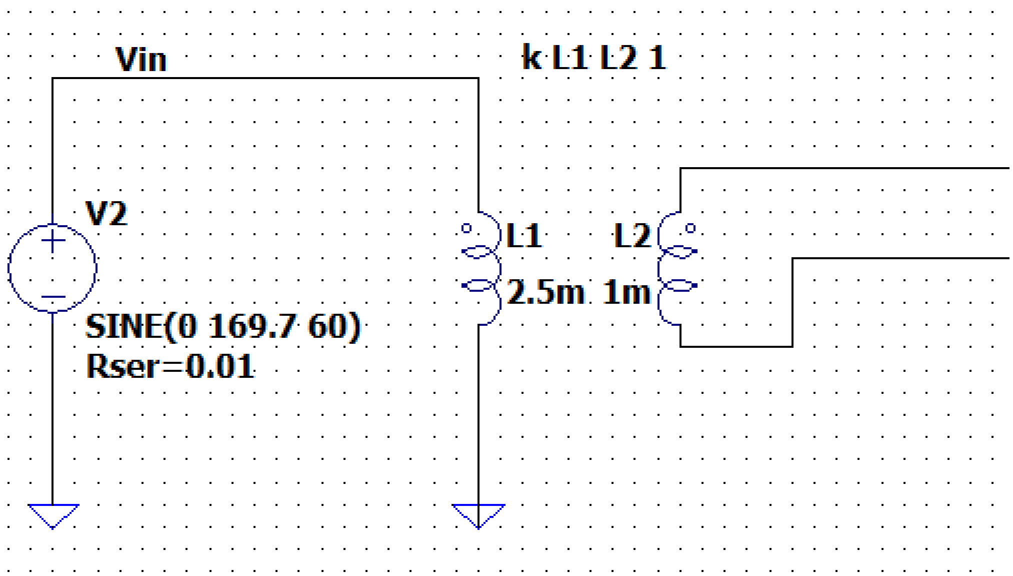


Figure (1) LTSpice transformer circuit.

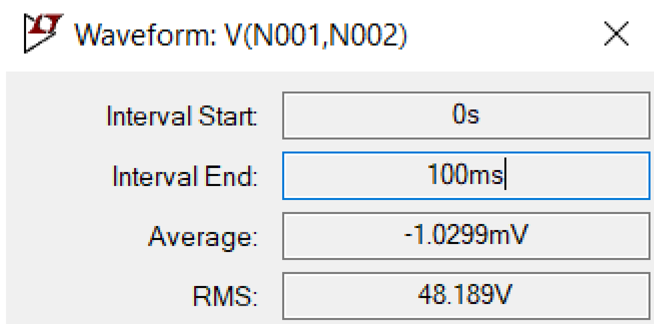


Figure (2) The output voltage.

As seen in the two figures above that the transformer is 1:1 and the input is 120V in RMS, which is $120\sqrt{2} = 169.7$. The frequency is 60Hz and the inductor values are found using the calculation above. In figure (2), the RMS is about 48 V as the ideal transformer. See ratings for the transformer in appendix (A) or in the attached datasheet for the given transformer.

Full-Wave Rectifier Circuit:

This full-wave bridge rectifier was designed based on the concept of how the diodes work. The current flows from high potential to low potential so during the first positive cycle only two diodes will be forward and during the negative cycle, only the other two diodes will be forward given the negative cycle; basically, the negative side of the AC side wave will be flipped over the x-axis creating a full-wave rectifier. This will be the output signal of the DC output or pulsated a DC signal without filtering or power factor corrected, which will be designed and discussed in the next sections.

The diodes selections are based on how high the current, voltage, and heat the diodes can handle. As the capacitors are existed to filter, the current will not pass through the capacitor while discharging. The capacitor is just storing and discharging the voltage, so the current will be high in the node before the capacitor, and this might result in burning the diodes. Following the steps below and choose the diodes from datasheets based on:

1- Maximum repetitive peak reverse voltage (V_{PRM}).
   120*1.414 = 67.9V in this case 100 V is enough for V_{PRM}.
2- Maximum average forward rectifier current. ($I_{F(AV)}$)
   The transformer is rated 2A and the diode is selected based on the load required which is 1A and is enough for the diode to handle, but if the load is more than that, the 30% extra amps is a good factor to choose.
3- Forward voltage drops (V_F).
   Two concerns about voltage drops are the voltage output of the diode will be dropped based on the voltage drop, for example, if VF = 0.6V and the input is 5 V, the output will be 5-0.6 = 4.4V and in this design the input voltage is high and the output is buck converter, so this concern is not necessary. The second concern is that the diode works like a heat sink that dissipates heat, for example, diode 1N4002 has a 1.1V forward voltage drop, so to calculate the heat, P = 1.1V*1A= 1.1W of heat generated from the full-wave rectifier at maximum current.

Capacitors' selection is based on the frequency, voltage drop, and the current drawn. The capacitor is chosen for the rectifier to smooth the voltage and get rid of the ripple voltage. The formula for choosing a capacitor is current half-cycle time / acceptable voltage drop = microfarad. For example, 1amp of current being drawn, 8.3ms of 60Hz AC half-cycle time, and voltage drop of 1.4. This results in $\frac{1\times 8.3}{1.4}$ = 5929 microfarads. This size is too high and is not available, so choosing the highest size of the available ones is good with considering ESR. See figure (3) for the full-wave rectifier circuit with PFC in the next section.

Power factor correction circuit (PFC):

The circuit of the PFC is selected to be Vally Fill Passive Power Factor Correction Circuit because it is simple and cheap regardless of the other sophisticated circuits that use control and switches. This circuit is used to pull power from the AC line when the line voltage is larger than a half percent of it is peak voltage.

There are two capacitors that are charged to 50 % of the AC peak voltage are connected in series with the diode the first diode and a small resistor on each half cycle of the rectified AC input. The other resistor is for reducing the peaks in the current waveform when the capacitors charge. The output current after the

To select the component values as the specification of this design as the following:

VAC = 120V, Vin minimum 48V = $\frac{\sqrt{2}\times 48}{2}$ = 34 V

At 60Hz, the full time of a half AC line cycle is 8.33ms.

The power is derived based on AC line voltage to be equal to or less than 50% of its peak voltage.

The holdup time for the capacitor t_{HOLD} = (1/3) × 8.33 = 2.77ms

The capacitors can be calculated $C_{TOTAL} = [\frac{P_{out}}{V_{in,min}} \times t_{HOLD}]/V_{drop}$

$C_{TOTAL} = \frac{\frac{5}{34}\times 0.00277}{20}$ = 20 uF

C1 = C2 = 10 uF

Note: The V_{drop} is set to 20V to avoid the need for large capacitors. This drop implies that the node voltage Vin at the input of the converter will drop to 40V during part of AC line cycle. See the reference for the citation.

The LTSpice simulation conducted the working circuit and the circuit in figure (3) below is the transformer, full-wave rectifier, and Valley Fill PFC circuit.

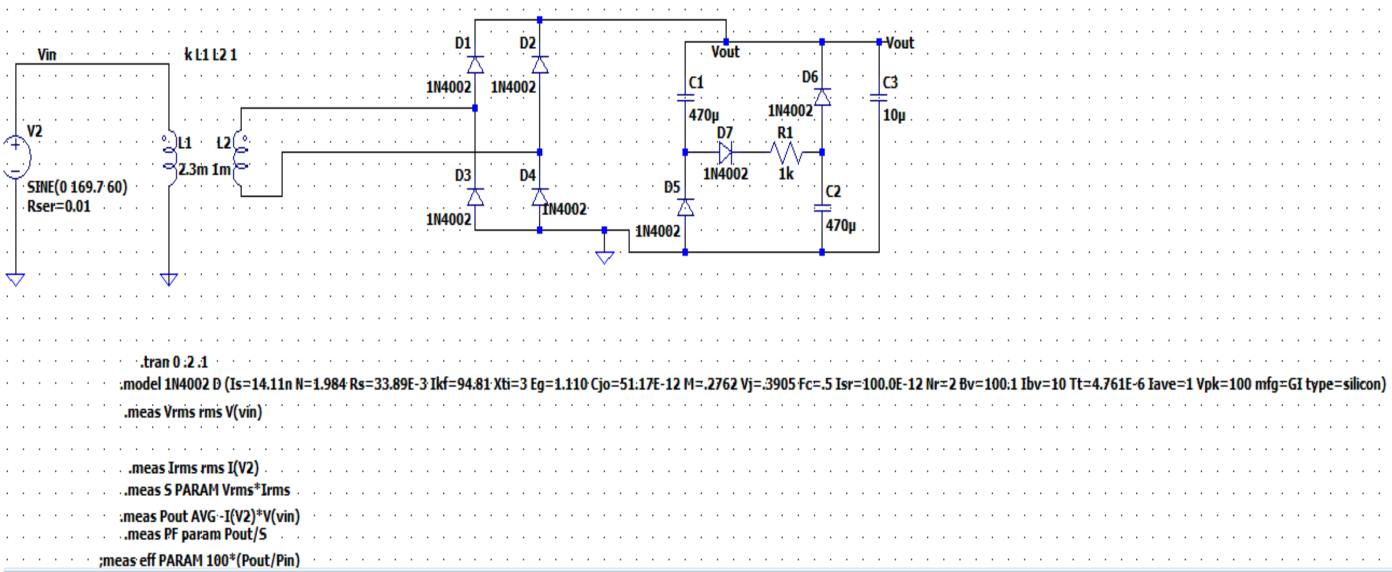


Figure (3) Vally Fill PFC circuit.

The circuit above is the complete circuit for Vally Fill PFC, full-wave rectifier, and AC source. The capacitor C3 in the output is to filter and to smooth the voltage output as seen the figure (4) below. The first plot is without C3, and the second plot is with C3.

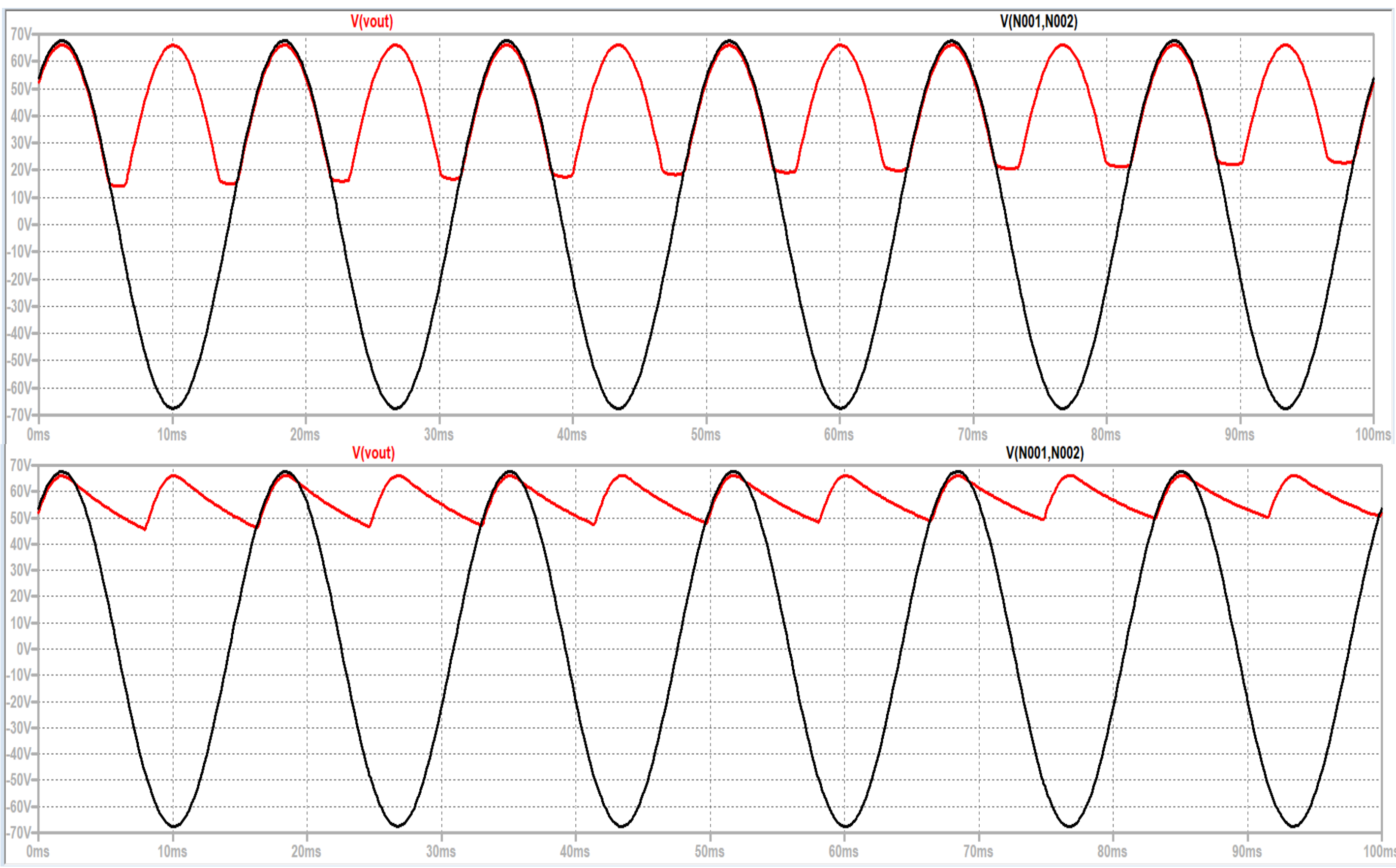
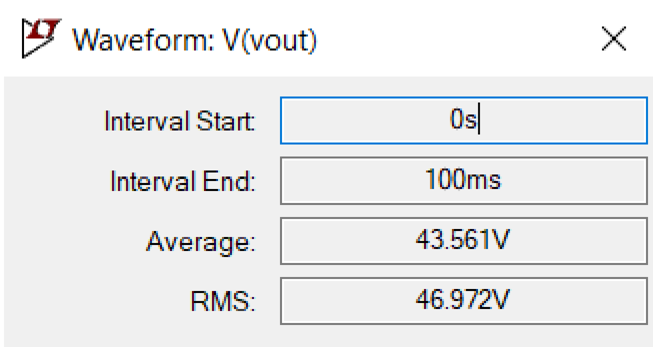


Figure (4) Top plot without C3 and the bottom plot with C3.

The output of the circuit is about 47V RMS and has a power factor of about 0.8 as seen the figure (5) below taking from LTSpice. The input power from the AC source is measured to be -7.9147KW. the negative sign indicates that the source is delivering power. I_{RMS} = 83.641A and V_{RMS} = 119.28V. So, to calculate the power factor PF= $\frac{average\ power}{I_{RMS}V_{RMS}}$ = 0.793.




```
vrms: RMS(v(vin))=119.284 FROM 0 TO 0.1
irms: RMS(i(v2))=83.6411 FROM 0 TO 0.1
pout: AVG(-i(v2)*v(vin))=7914.72 FROM 0 TO 0.1
s: vrms*irms=9977.04
pf: pout/s=0.793294
```

Figure (5) LTSpice measured values.

Voltage Regulator DC-DC Switching IC Regulators: (Buck converter)

This converter is an integrated circuit for a DC-DC buck converter. The IC is selected based on the specification of 48 V RMS and DC output of 5V and 1W. The selection is chosen to have an IC that has high voltage to $48\sqrt{2}$ = 67.88V peak voltage. Based on the peak voltage, the IC is chosen to have a high input voltage of 71V to 5V output. Also, the current output of 1A gets 5W when connecting the output with a load resistor of 5 Ω.

It was chosen two IC chips that have the description of this design. The IC number BD9G341AEFJ-E2 is a DC-DC switching regulator and the second one is MAX5035BASA this IC is tested and simulated. See appendix (B) for MAX5035 data and simulation. For BD9G341 has the following descriptions:

1- It is a step-down buck converter
2- Voltage input minimum of 12V.

3- Voltage input maximum of 76V
4- Voltage output minimum of 1V.
5- Current output of 3A.
6- Switching frequency 50khz to 750kHz
7- Surface mount.
8- Package 8-SOIC (0.154", 3.90mm Width) Exposed Pad.

See the datasheet for more information.

The external components of this IC are based on the datasheet. See figure (6) below for a typical application schematic taken from the datasheet for the BD9G46 IC buck converter.

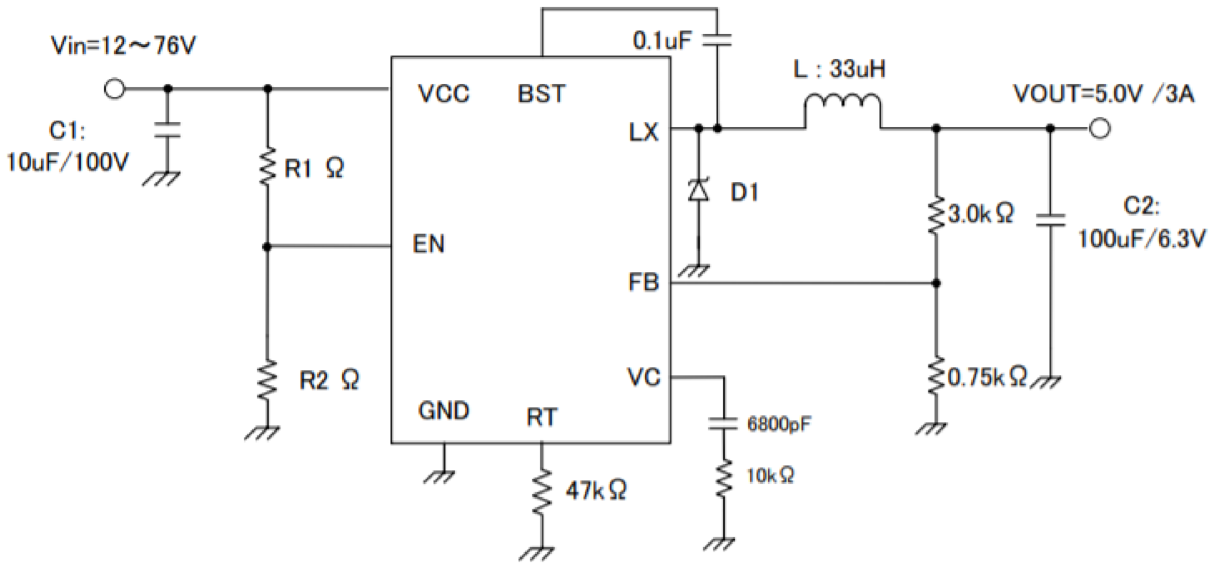


Figure (6) Typical application schematic.

The size of the elements is selected based on the datasheet as seen in figure (6) above. For R1 and R2 which are connected from pin EN is Shutdown pin to the input pin VCC. If the voltage of this pin is below 1.3V, the regulator will be in a low power state. If the voltage of this pin is between 1.3V and 2.4V. The IC will be in standby mode. If the voltage of this pin is above 2.6V, the regulator is operational. See the formulas below to find R1 and R2 which found to be R1 = 100kΩ and R2 = 20 kΩ.

$$R1 = \frac{Vuvhys}{IEN} \quad [ohm]$$

$$R2 = \frac{VEN \times R1}{Vuv - VEN} \quad [ohm]$$

This circuit is built in Pspice software because it doesn't have modal in LTSpice. See figure (7) below for the circuit built in Pspice.

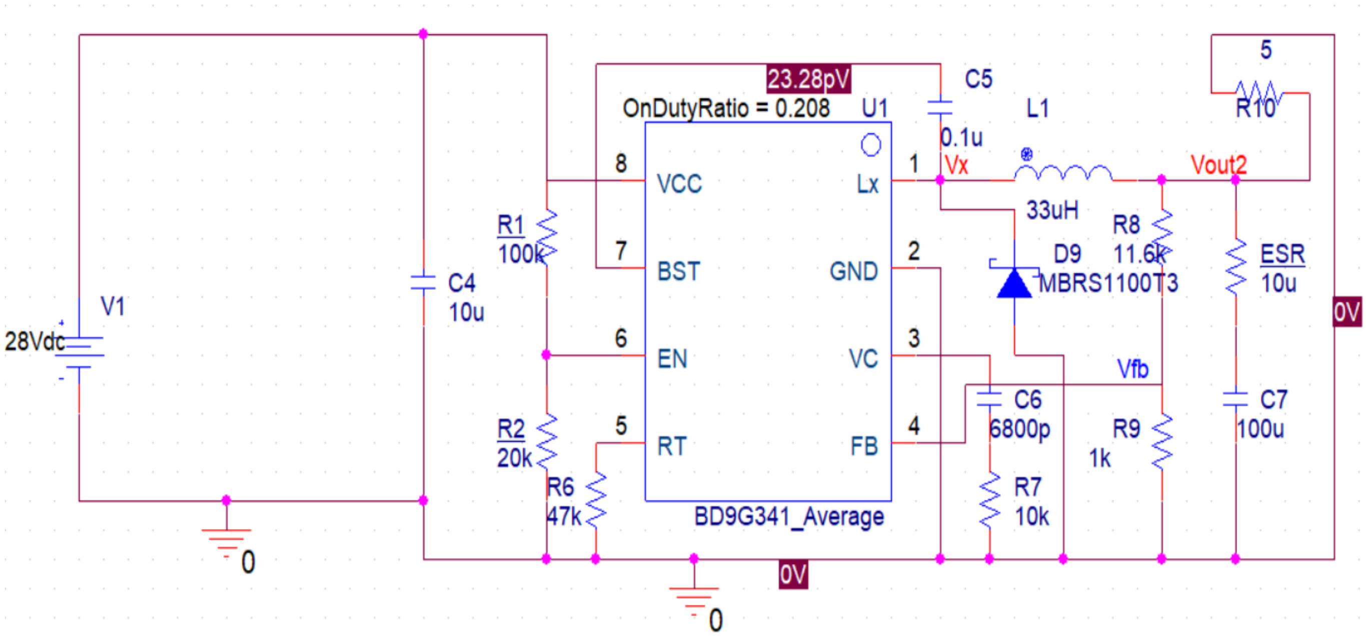
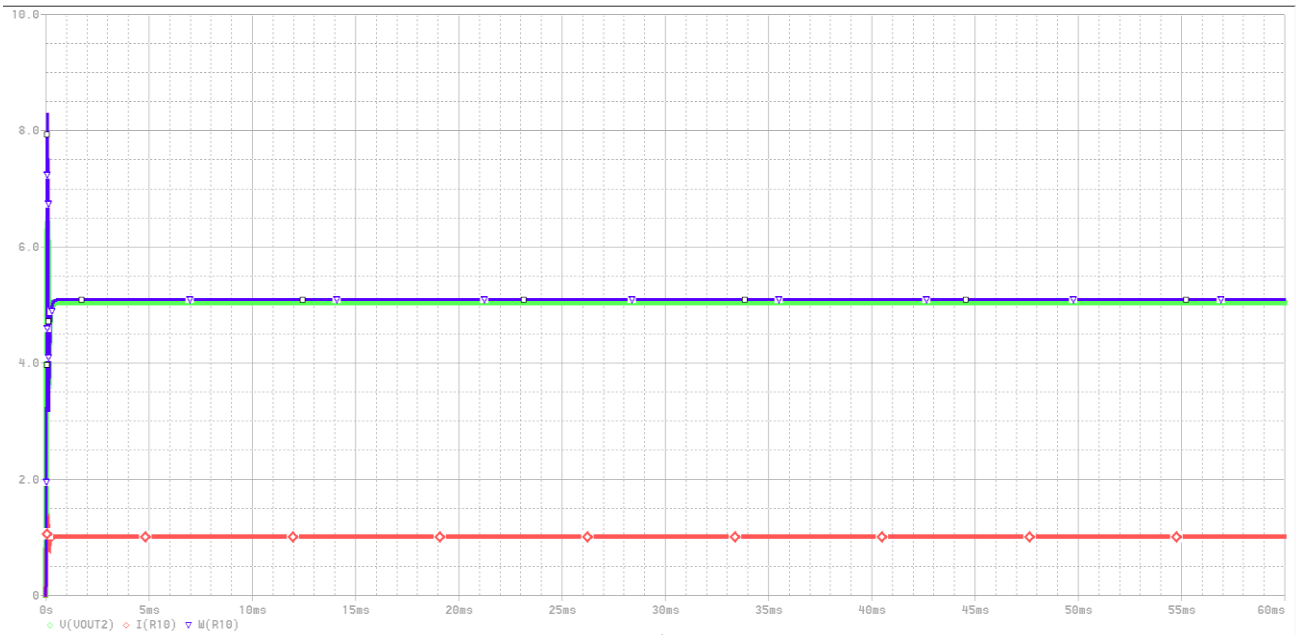


Figure (7) Pspice DC-DC Buck Converter.

The circuit above is built in Pspice and simulated using Pspice. The results appeared to be the correct results that meet the requirements of this design. This circuit is built in the lab and it will be discussed in the lab section below. The measurement for simulating this circuit is placing the voltage, current, and power probes in their specified nodes. For the output voltage, the probe is placed in the node after the inductor. The current probe is placed right before R10 which is the load resistor. The power probe is placed in the load resistor R10.

The plot in figure (8) below shows the plots for the voltage, current, and power outputs. The green plot is output voltage of 5V, and the blue plot is the power in the load resistor, which is 5W, and the red plot is the output current, which is 1A. Also, the accurate values of these plots are shown the table right below the plots.



Trace Color	Trace Name	Y1	Y2	Y1 - Y2		Y1(Cursor1) - Y2(Cursor2)		0.000		
	X Values	10.511m	10.511m	0.000		Y1 - Y1(Cursor1)	Y2 - Y2(Cursor2)	Max Y	Min Y	Avg Y
CURSOR 1,2	V(VOUT2)	5.0415	5.0415	0.000		0.000	0.000	5.0415	5.0415	5.0415
	I(R10)	1.0083	1.0083	0.000		-4.0332	-4.0332	1.0083	1.0083	1.0083
	W(R10)	5.0833	5.0833	0.000		41.795m	41.795m	5.0833	5.0833	5.0833

Figure (8) Pspice Voltage, Current, and Power outputs plots with their values.

Other simulation plots are followed and taken from the datasheet. In figure (9) below shows the switching frequency / VOUT ripple for 10ms transient. The simulation is for 5V output and 1A output current. The switching frequency is 201KHz and V_{out} ripple is 7.1mV. The results depend on some dynamic characteristics of external components, input signal speed, PCB and how close the components are to the IC.

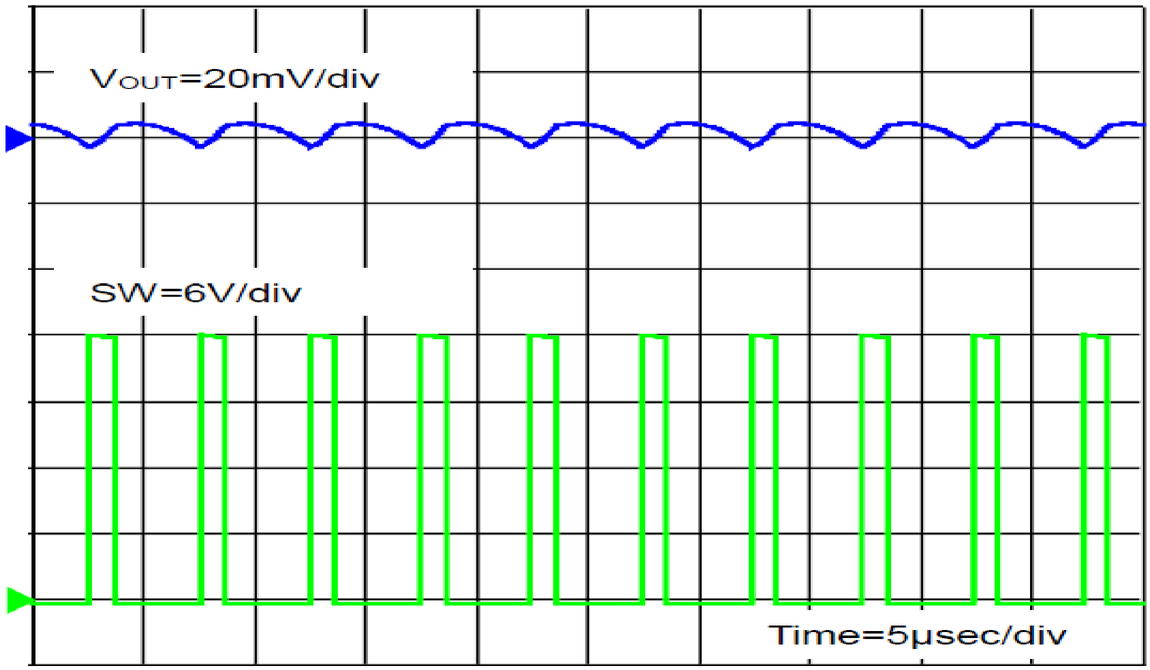


Figure (9) Pspice V_{out} Ripple.

In figure (10) below shows the inductor ripple current for 10ms transient. The simulation is for 5V output and 1A output current. The inductor ripple is 640mA. Also, the results depend on some dynamic characteristics of external components, input signal speed, PCB and how close the components are to the IC. The inductor specification of the current rating and other non-idealities have an impact on the result.

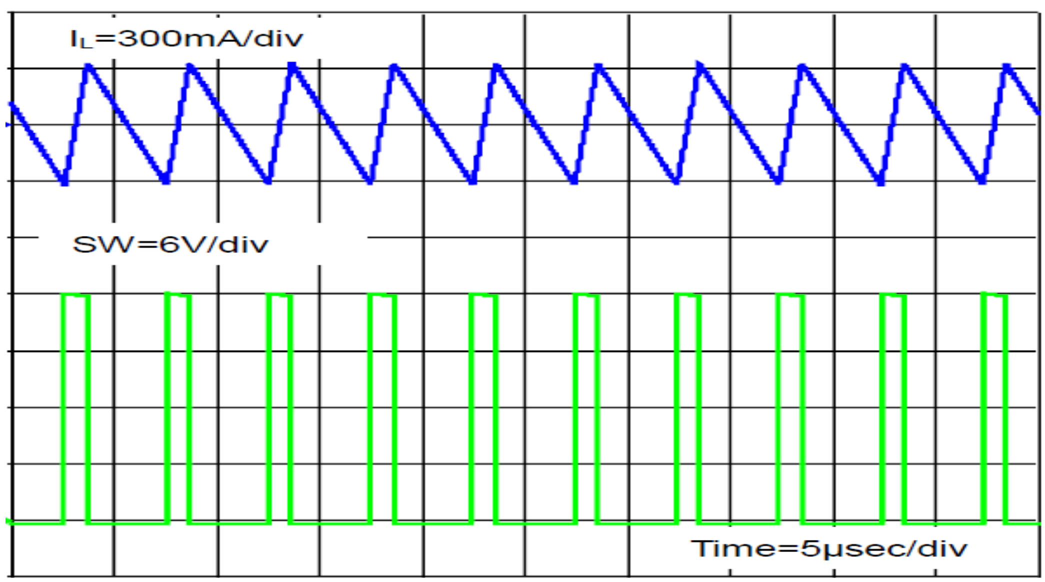


Figure (10) Inductor Ripple Current.

In figure (11) below shows the soft-start time for the simulation of pin LX at node V_X for 120ms transient. The simulation is for 5V output and 1A output current. As seen from the plot the switching in the pin LX starts when the pin EN which is the shutdown pin goes above 2.6V for its operational mode, then the output voltage starts to rise with switching in LX pin as seen in the green plot for the switching. The soft-start time is 20ms with EN rising to FB = 0.85V. Also, the results depend on some dynamic characteristics of external components, input signal speed, PCB and how close the components are to the IC. The inductor specification of the current rating and other non-idealities have an impact on the result.

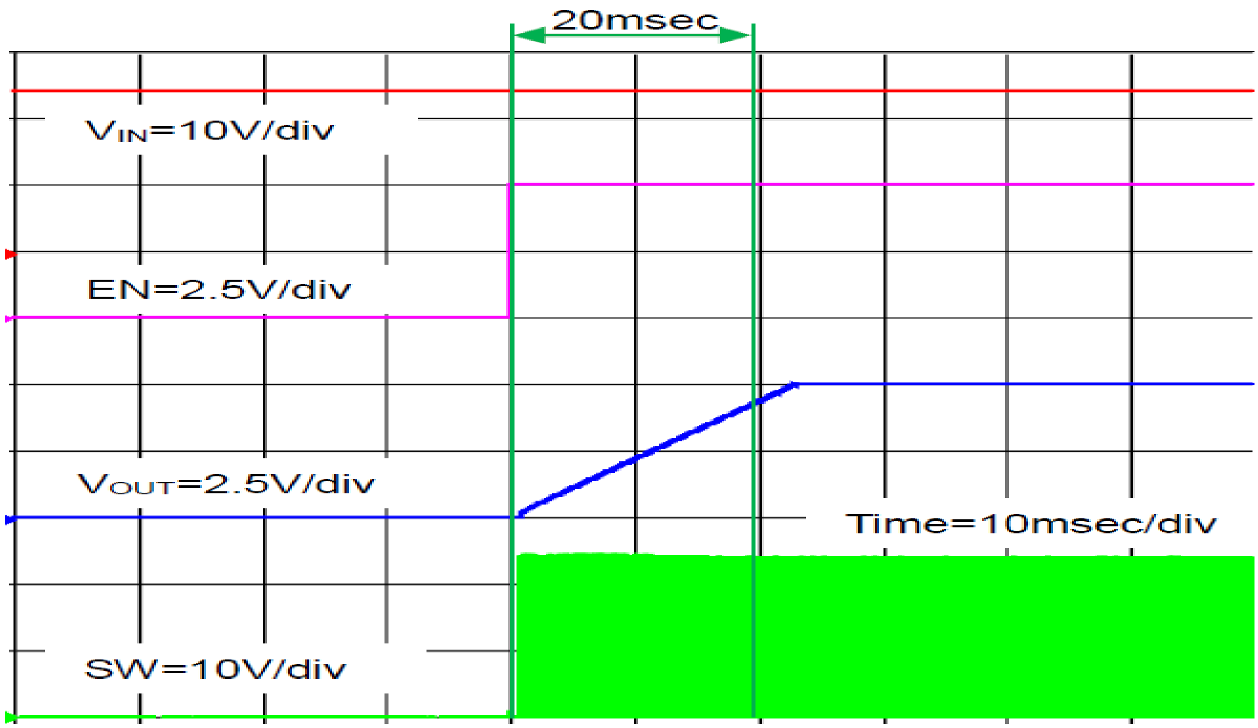


Figure (11) Pspice Soft Start Plot.

In Lab Experiment:

After going through the steps for design and simulation as explained above, the circuit was built in the lab following the same procedures for testing each part. The testing started with a transformer to see the output voltage and was found to be 56V RMS. Second, the full-wave rectifier was built and tested. Third, the Vally Fill PFC was built and tested. Finally, the regulator buck converter was tested separately using a DC power supply to make sure it works.

The transformer is an ideal transformer; it was tested using the oscilloscope to see the output and its sine wave. See figure (12) for the measurement taken for the transformer.

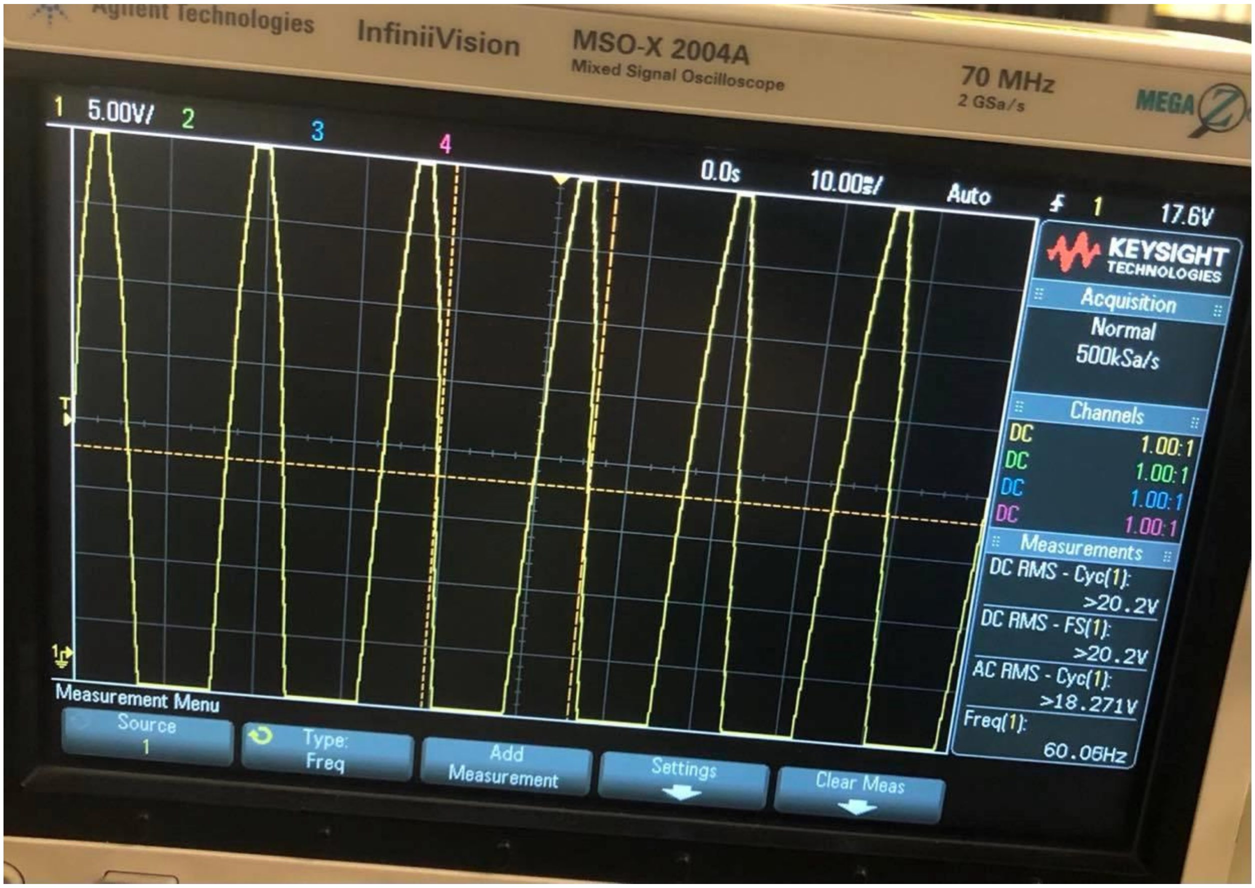


Figure (12) Transformer Measurement.

From the figure (12) above, it indicates the frequency is 60Hz, the AC RMS is higher than 20V. The oscilloscope plotting the wave and output voltage and are not accurate because of the oscilloscope limitation. See appendix (A) for the datasheet of the transformer.

The full-wave rectifier was built on the breadboard using diodes 1N4002 that has 100V reverse voltage and 1A reverse current. The rectifier was tested using the oscilloscope and it appears it rectifies the signal and the capacitor filtering the ripples. See figure (13) below for the oscilloscope plot taken in the lab. It shows the green plot which is rectified and filtered comparing to the yellow input plot. See figure (14) for the full-wave bridge rectifier circuit built in the lab.

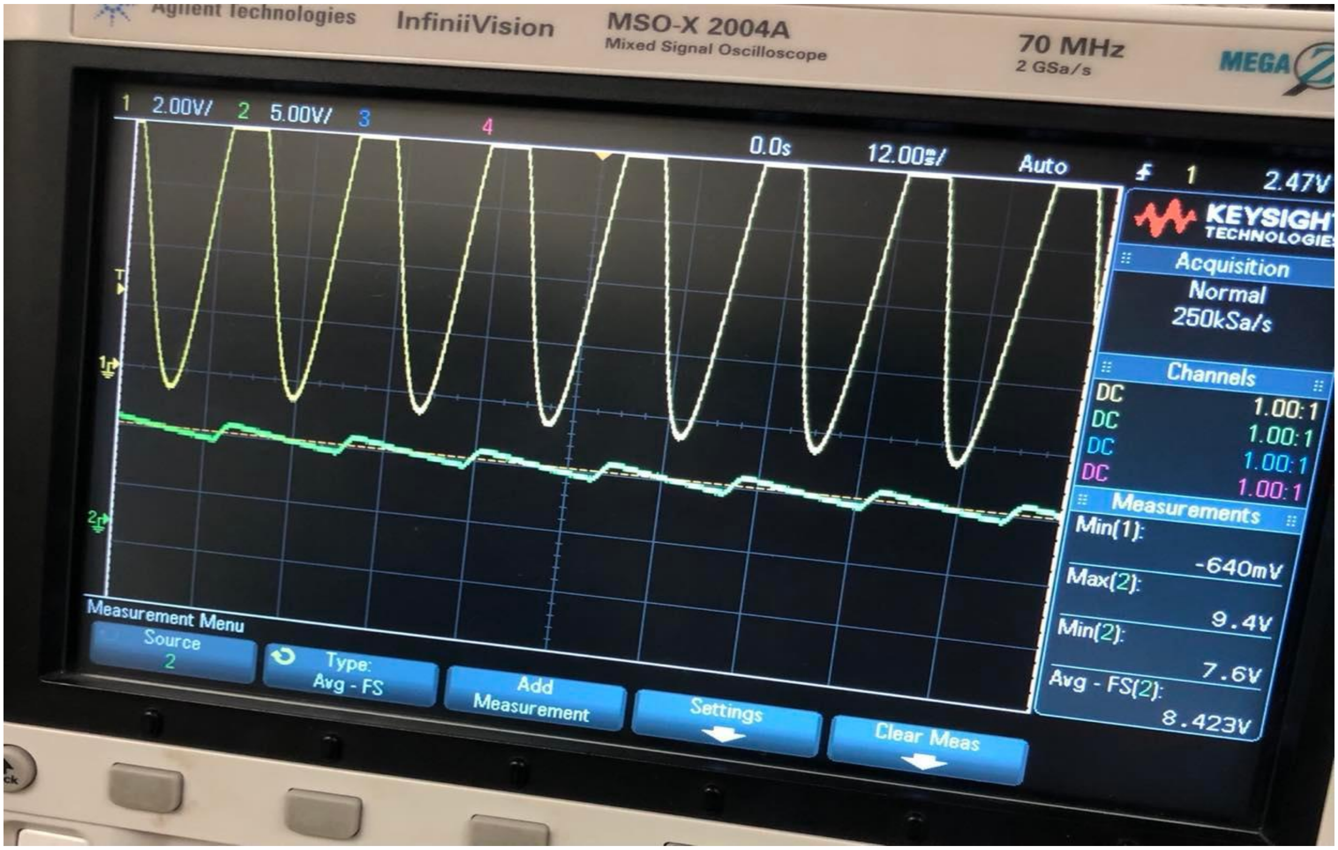


Figure (13) Rectifier Measurements.

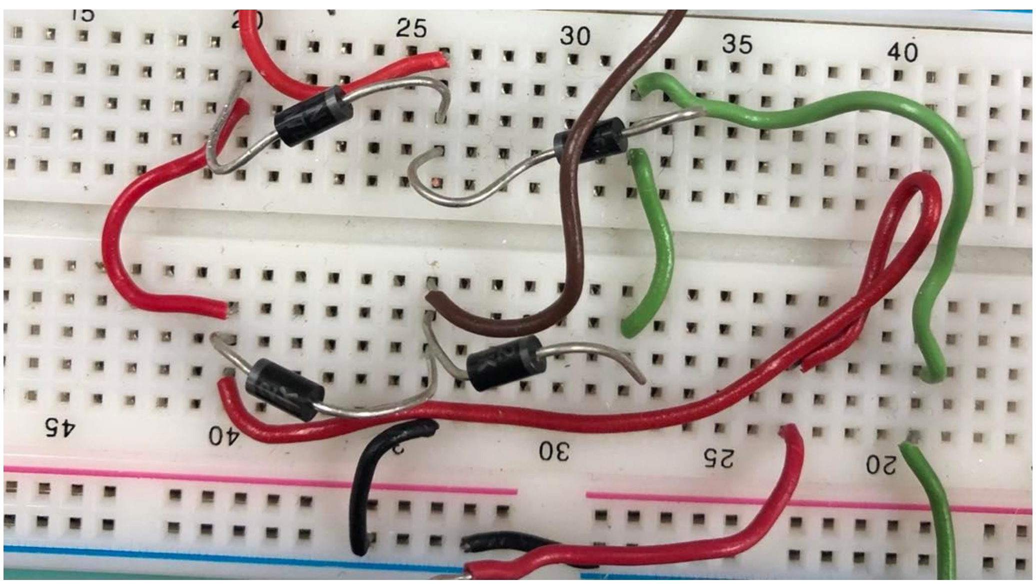


Figure (14) Full-Wave Bridge Rectifier Circuit.

The circuit was built in the breadboard using four rectifier diodes 1N4002 with 100V reverse and forward voltage of 0.6V, and reverse current of 1A. The circuit was tested and measured using the oscilloscope as seen in figure (13) above.

The Vally Fill PFC circuit was built in the breadboard and tested using 28V RMS. The circuit worked as expected, but only the switching didn't fit the switch of the buck converter. This will be discussed later in the discussion section. The oscilloscope plot of the Vally Fill circuit is shown in the figure (15) below.

Figure (15) Vally Fill PFC circuit Plot.

The figure above shows the plot for the PFC and indicates that the frequency is 120Hz as expected of doubling the 60Hz. Also, the DC output voltage is 28.8V. See figure (16) below for the circuit of PFC with full-wave rectifier connected in the breadboard.

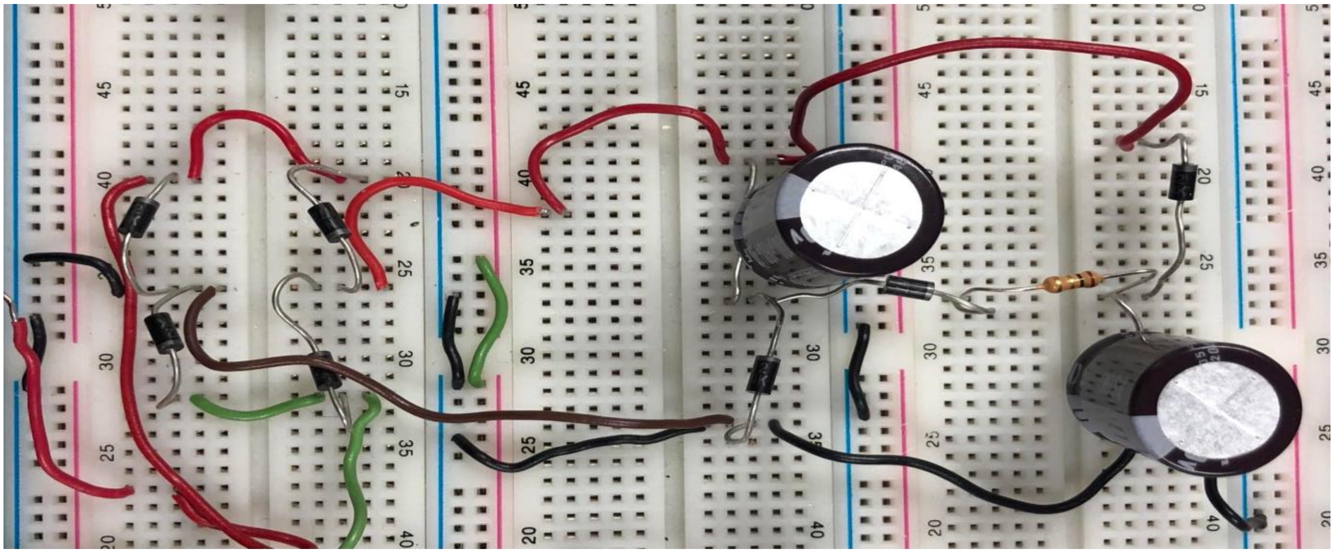


Figure (16) Vally Fill PFC with the rectifier.

The PFC part contains two capacitors rated 160V and 347Uf connected in series with two diodes 1N4002. This circuit is explained in the design section. The ground is connected with the common ground of the bridge rectifier as shown; the black wire is the ground for PFC and the brown wire is coming from the rectifier circuit ground to the PFC circuit ground.

Finally, the regulator buck converter IC was built and soldered in a PCB board and tested separately using a DC power supply to make sure it works. The circuit worked and resulted in an output voltage of 5V. See figure (17) which shows 5V using an oscilloscope.

Figure (17) Output voltage of 5V testing for DC-DC buck converter.

After testing the circuit and making sure that the circuit output is 5V, it was time to use the AC source from the transformer and the previously tested rectifier and PFC circuit. The output of the PFC circuit is the input of the buck converter BD9G41. After supplying the buck converter, it seems that the output doesn't work perfectly due to some reasons that will be discussed in the discussion section later. The results were good, and the output voltage was 5V, but when connecting the circuit with a load resistor of 5Ω to get 5W, the circuit resulted in about 2.8V instead of 5V. This means that the current is less than 1A. However, the requirement of 5W was almost met, but due to the lack of time and elements availability, the circuit is excepted because the circuit worked perfectly, and the issues occurred due to other factors mentioned in the discussion section. See figure (18) below for the plot of the switching nodes and the output of 5V

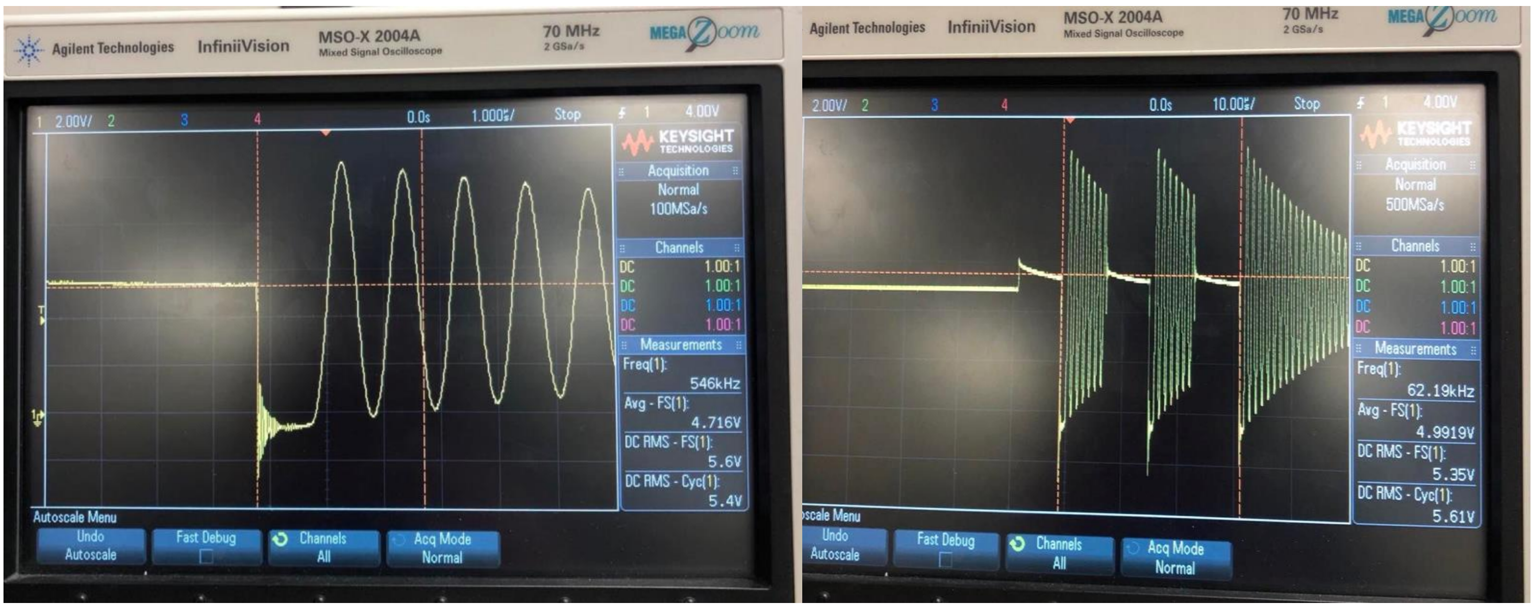


Figure (18) Switching plots and output voltage of the buck converter.

The plots above show the 62KHz with 5V and 546kHz of average 4.71V. The switching doesn't seem accurate as the simulation has a switching frequency of 201kHz. Since the output of 5V goes down to 2.8V when connected the output with a load resistor, the switching doesn't seem to be correct and compatible with the IC. Also, See figure (19) for the soldered buck converter circuit.

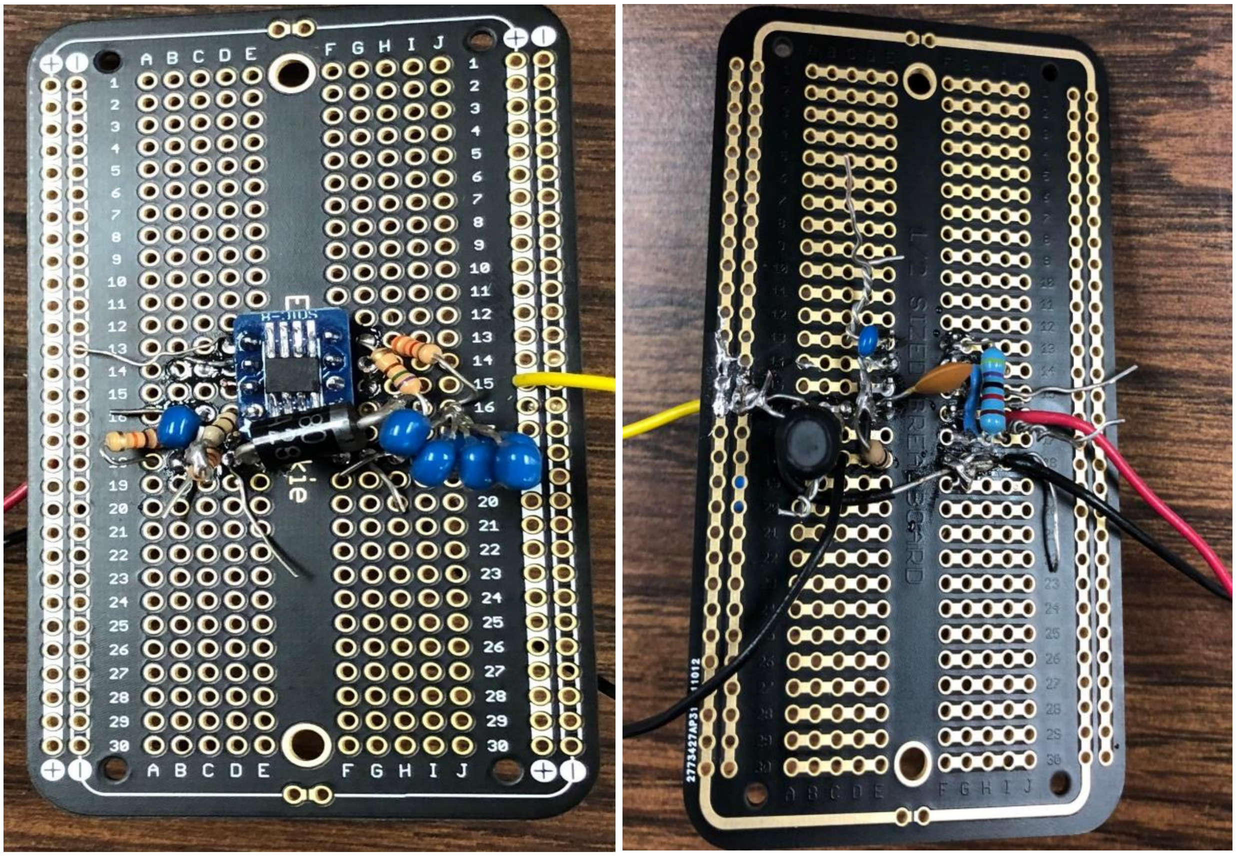


Figure (19) Soldered Buck Converter Circuit.

The circuit above was soldered and connected the components as close to the IC as possible. The red wire is the input that comes from the PFC and the black wire is the common ground. The yellow wire is the output of the buck converter. The components were soldered on both sides of the PCB to avoid contact with other components due to their size.

Analysis and Discussion

This Final project specification for the power supply was implemented and designed as required and it is met the specification with the correct results of the IC, except the power of 5W, which was not perfect because of switching issues. As mentioned in the lab experiment section above that the output voltage is 5V, but when connecting the 5Ω load resistor, the voltage goes down to 2.8V and the current is about 0.52A. In the beginning, the IC was soldered in a small PCB and the external components were connected to the breadboard. The output voltage value was 5V, but when installing the load resistor, the voltage disappears, and the current is less than 0.2A because the components are a little further from the IC and causing some delay in storing and discharging the capacitors and some internal switching issues. After the circuit was soldered in PCB with its external components as close to the IC as possible, the circuit worked perfectly. It gets about 0.52A of the output voltage of 2.8V when installing the 5Ω load resistor. After multiple trial and error tests, the issue was found to be in the Vally Fill PFC circuit. The switching of the PFC was not compatible with the switching of the IC. See figure (20) for the switching plot of the output of the PFC and the IC.

Figure (20) PFC and the IC switching output.

As seen in the plots in figure (20) above, the green plot decrease, the switching of the yellow plots stops at a specific frequency that generates less voltage than the threshold voltage of the buck converter IC, which causes the IC to go low power state or standby mode. AS indicated in the datasheet for pin EN “Shutdown pin. If the voltage of this pin is below 1.3V, the regulator will be in a low power state. If the voltage of this pin is between 1.3V and 2.4V. The IC will be in standby mode. If the voltage of this pin is above 2.6V, the regulator is operational. An external voltage divider can be used to set the under-voltage threshold. If this pin is left open circuit. when the converter is operating. This pin outputs 10uA source current. If this pin is left open circuit, a 10uA pull-up current source configures the regulator fully operational.” There might be other factors like internal error amplifiers, MOSFETS, and so on that causes the IC to stop working. This information needs more research to figure out how to fix the PFC that caused this issue, for example, finding perfect capacitors with specific ESR, might solve the issue. As known, the Vally Fill Passive PFC is simple and cheap, but old compared to sophisticated, complex PFC that use control switches, MOSFETS, and other controlling components. However, the problem was detected, and it can be solved by fixing the PFC output using other methods instead of the Vally Fill circuit.

Overall, all these results and most of the required specifications were achieved, it can be determined that the system project was successfully designed and implemented. Most requirements given for this system were met as expected and the issue found was related to PFC, not the IC circuit. The project was interesting, and the lesson is learned.

Important things learned:

The most important thing was learned in this project was how to purchase components online and understand the datasheets. This skill was learned from the project when purchasing components, the components must fit the design requirement.

Conclusion:

In conclusion, design a DC-DC Buck Converter Power Supply from an input transformer 115/48 V RMS was designed, simulated, and built successfully. The required results of the system were obtained and the issues of the problems that occurred were found, and they can be solved in the future.

Acknowledgment:

I would like to thank Dr. Tim Vogt for teaching us the skills of how to design the whole system with brilliant ideas that will help us in the future and providing us the sources and ideas of how to detect, solve the problems, how to solder and how to purchase the components online.

References

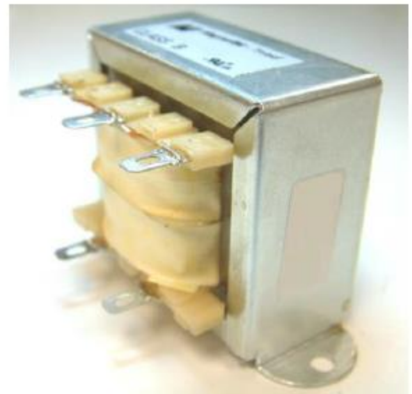
1- IC: BD9G341AEFJ-E2 datasheet.
2- F8-48 Quick Pack small power transformer datasheet.
3- https://www.powerelectronicstalks.com/2018/10/valley-fill-passive-power-factor-correction-method.html

Appendices

A. Transformer Datasheet Info.
B. IC: MAX5035BASA+T.

A. Transformer Datasheet Info:

F8-48

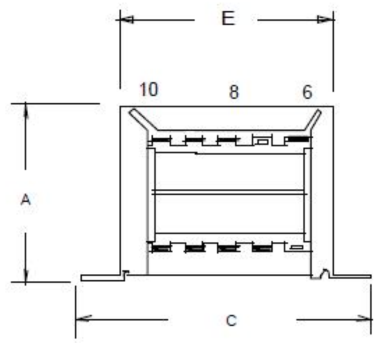


Description:
The F8-48 Quick Pack small power transformer offers a significant reduction in size and weight over a standard transformer. This transformer can be used for a wide variety of applications. It is bobbin wound for reduced size and small operating space.

Electrical Specifications (@25C):
Maximum Power: 100.0VA
Input Voltage: 115VAC@50/60Hz
Output Voltage: 48.0VCT@2.0A
Hipot: 2500VAC primary to secondary; 1500VAC windings to core.

Construction:
Split bobbin non concentric winding eliminates costly electrostatic shielding.
Termination is suitable for quick connects or soldering.
Built with UL Class B Insulation System.

Safety:
UL: File E53148, UL 5085-1 and 2 (formerly UL 506), General Purpose.

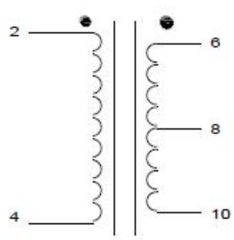


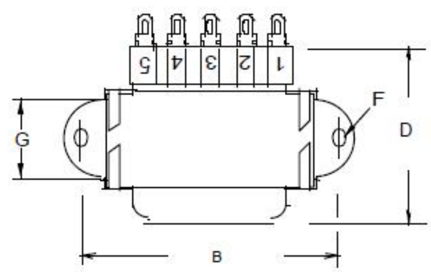
Dimensions:

A	B	C	D	E	F	G
2.562	3.562	4.031	2.250	3.062	.187 Dia	1.312

Notes: 1. Units: inches.
2. Terminal size: .187" X 0.021".
3. Weight: 2.75 lbs

Schematic:

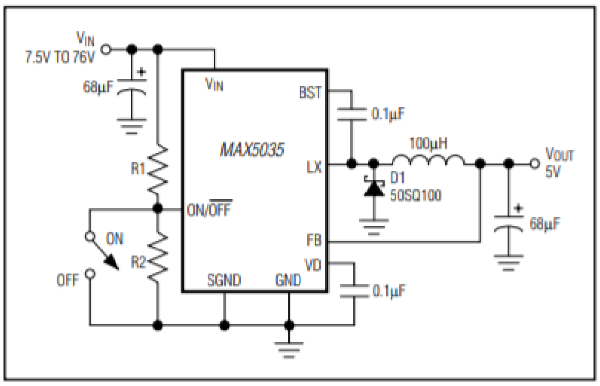


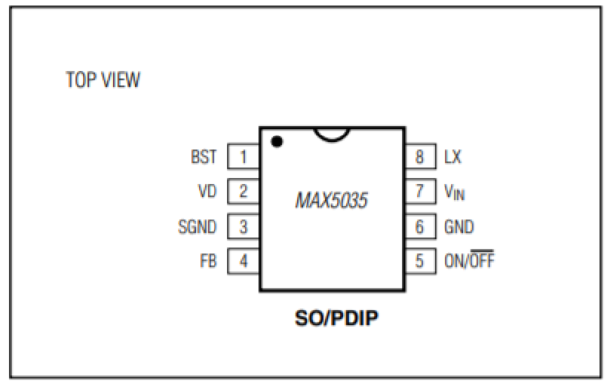


Input: 2 to 4
Output: 6 to10

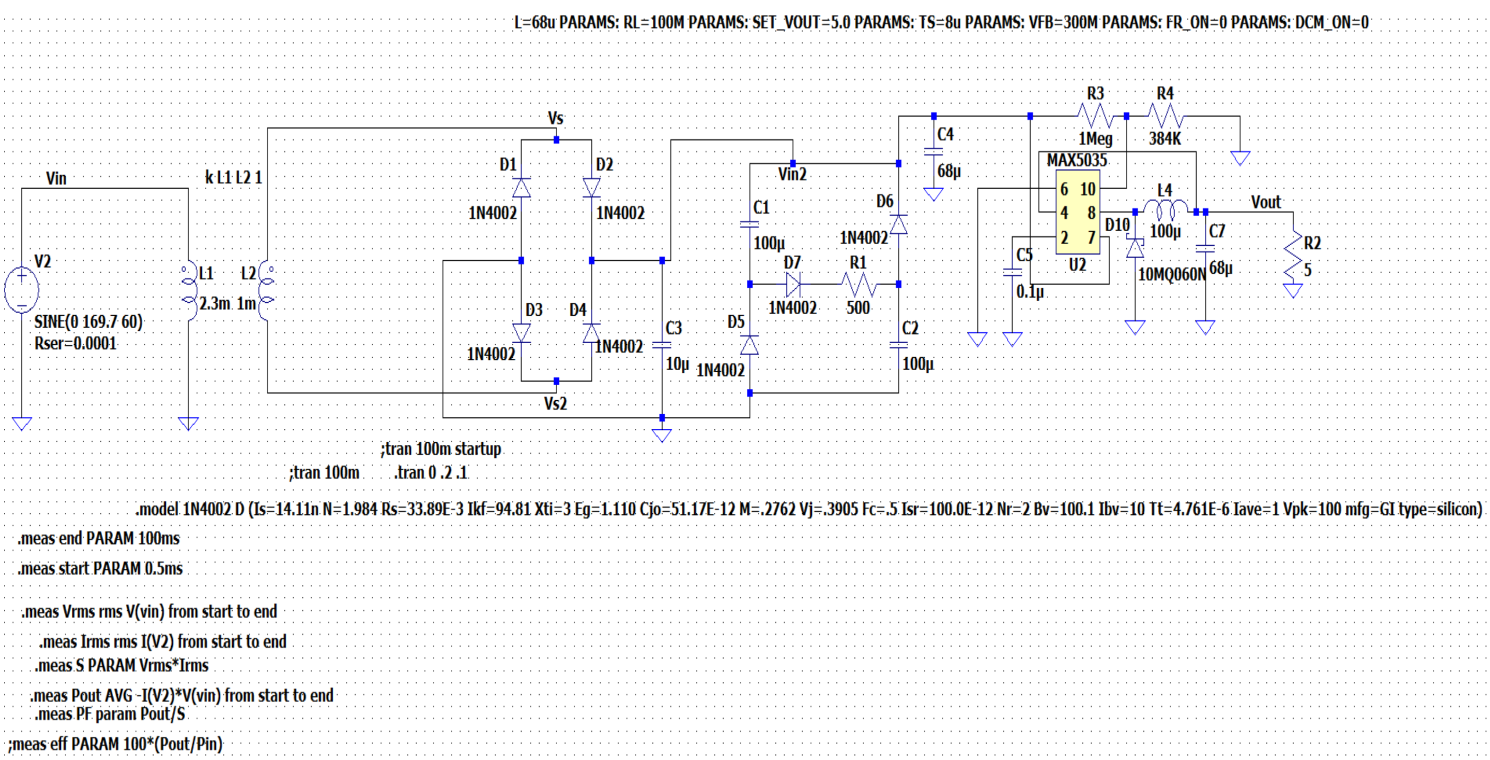
B. MAX5035BASA+T:
This IC was simulated and built in the lab and the results were found to be similar to the IC BD9G341. Below are the LTSpice circuit, plots, circuit built and results.
The IC MAX5035BASA description:
♦ Wide 7.5V to 76V Input Voltage Range.

- ♦ Fixed (3.3V, 5V, 12V) and Adjustable (1.25V to 13.2V) Versions.
- ♦ 1A Output Current.
- ♦ Efficiency Up to 94%.
- ♦ Internal 0.4Ω High-Side DMOS FET.
- ♦ 270µA Quiescent Current at No Load, 10µA Shutdown Current.
- ♦ Internal Frequency Compensation.
- ♦ Fixed 125kHz Switching Frequency.
- ♦ Thermal Shutdown and Short-Circuit Current Limit.
- ♦ 8-Pin SO and PDIP Packages.

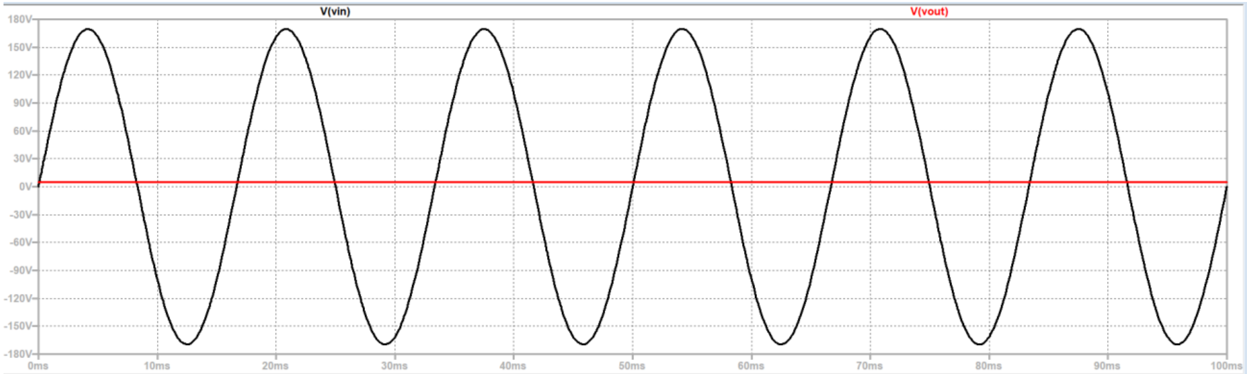


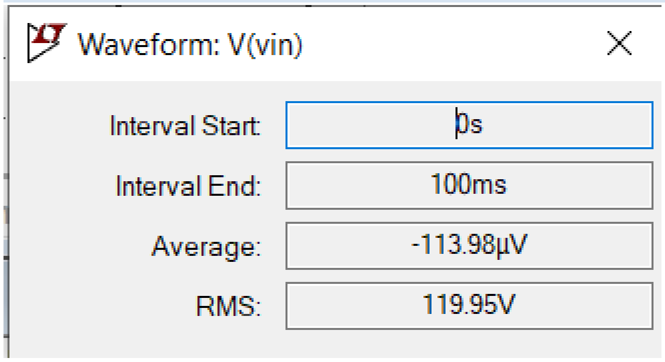


LTSpice Simulation:

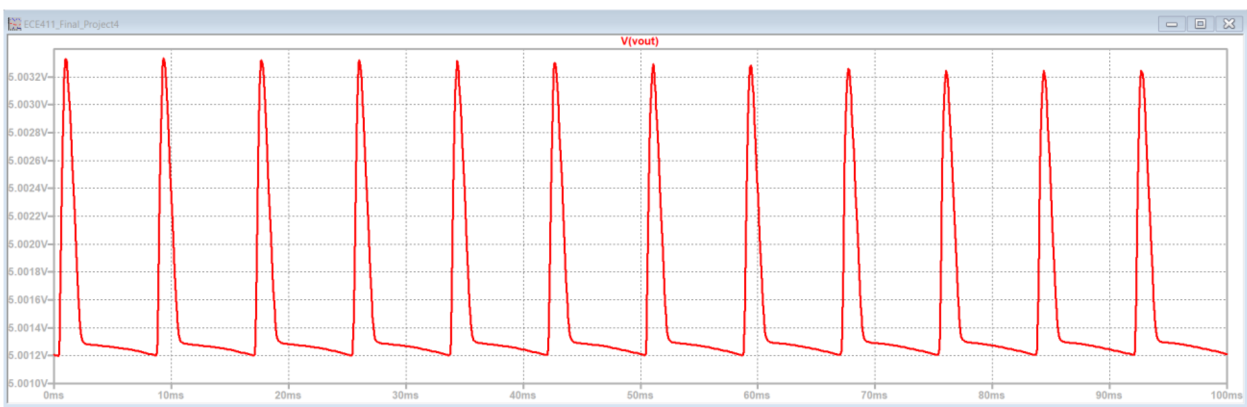


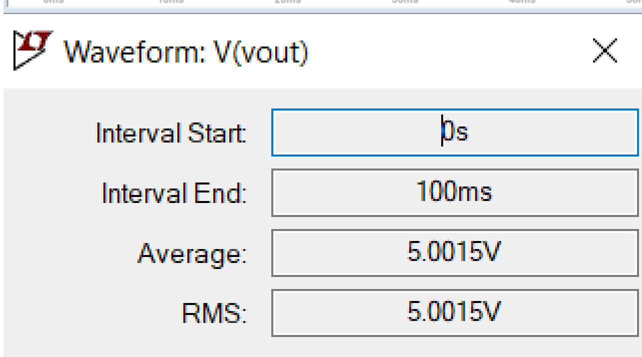
Input AC source plot and value:



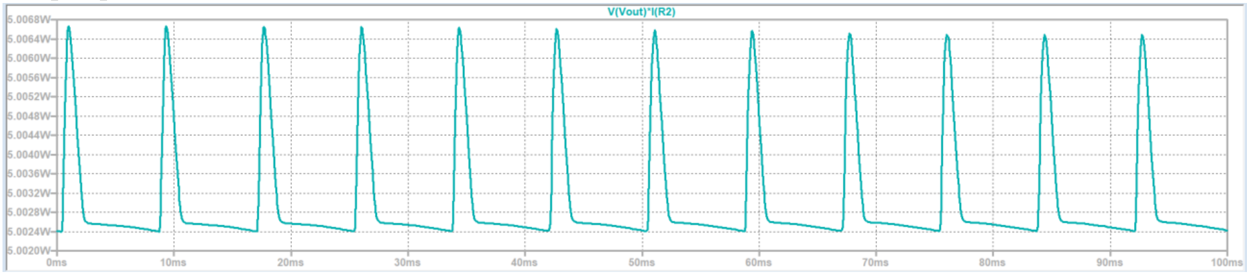


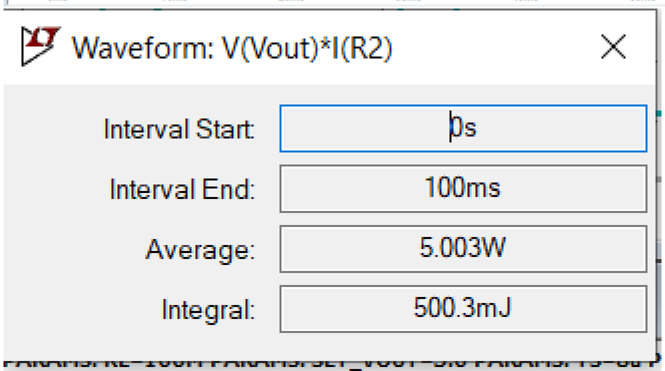
IC output plots and values:
Output voltage:



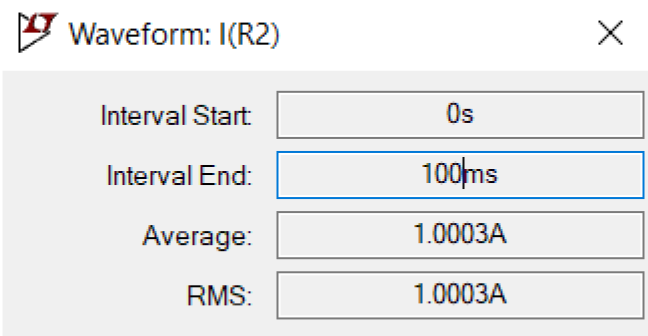


Output power:

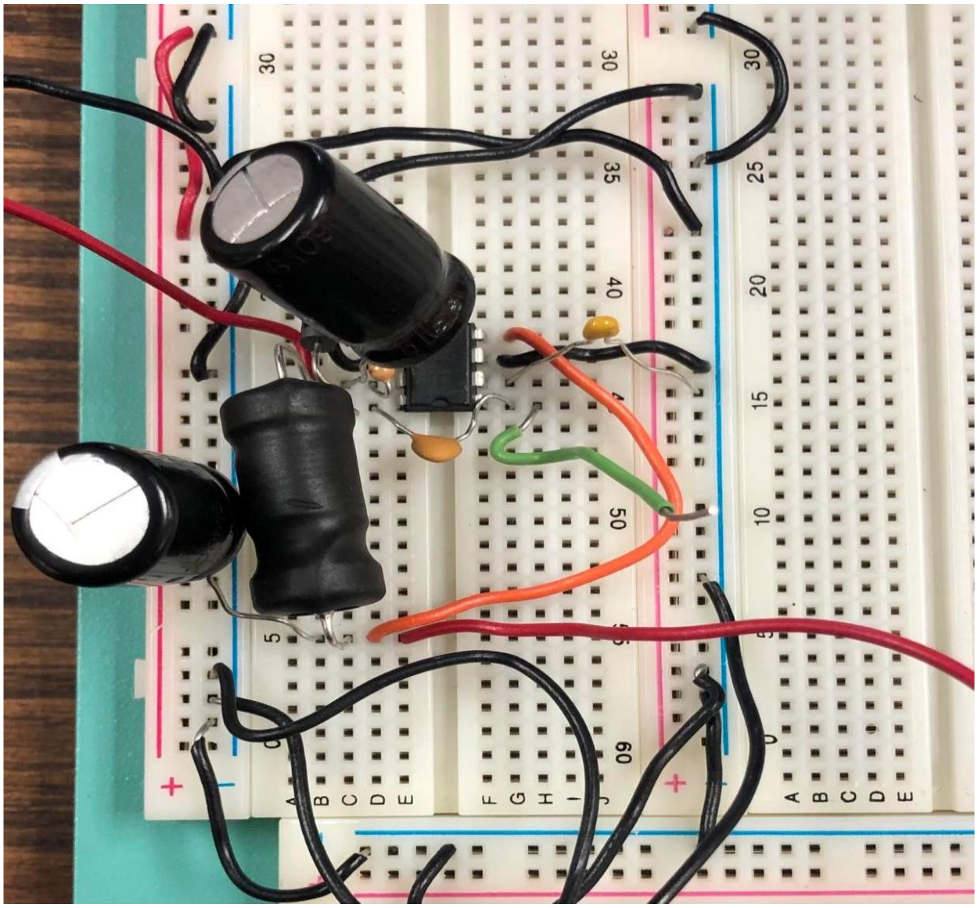


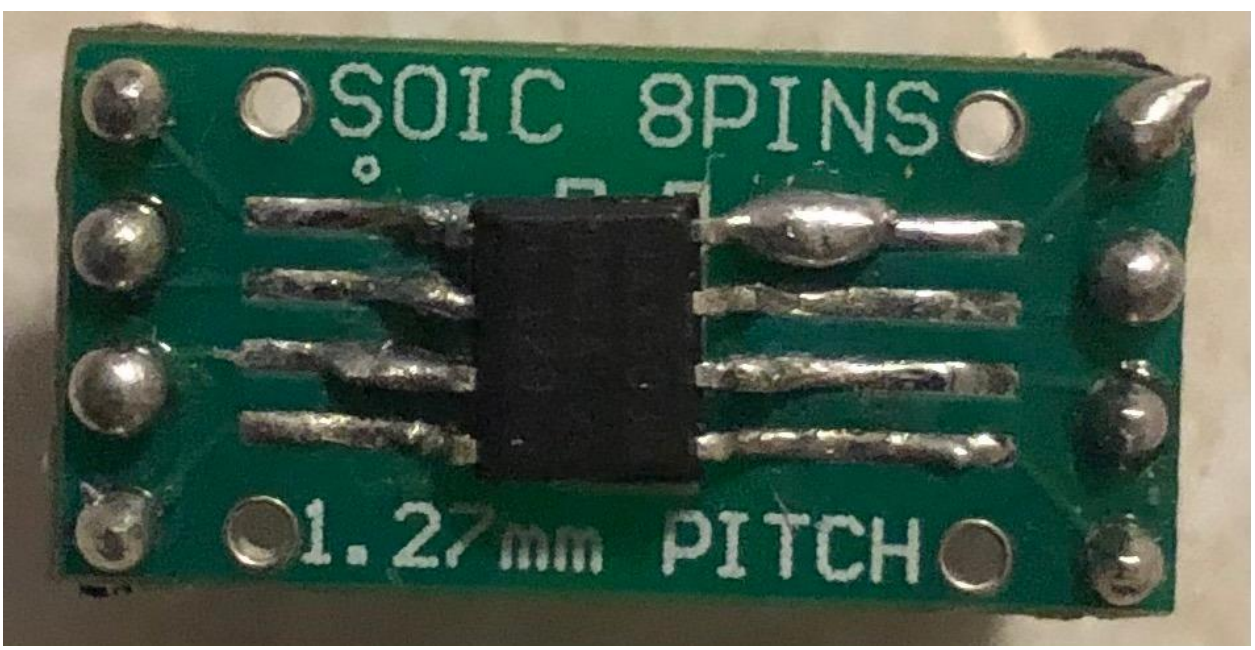


Output Current:



IC MAX5035 built in the lab:




SOIC 8PINS
1.27mm PITCH