AC-DC Flyback Converter

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ECE 511 Final Project
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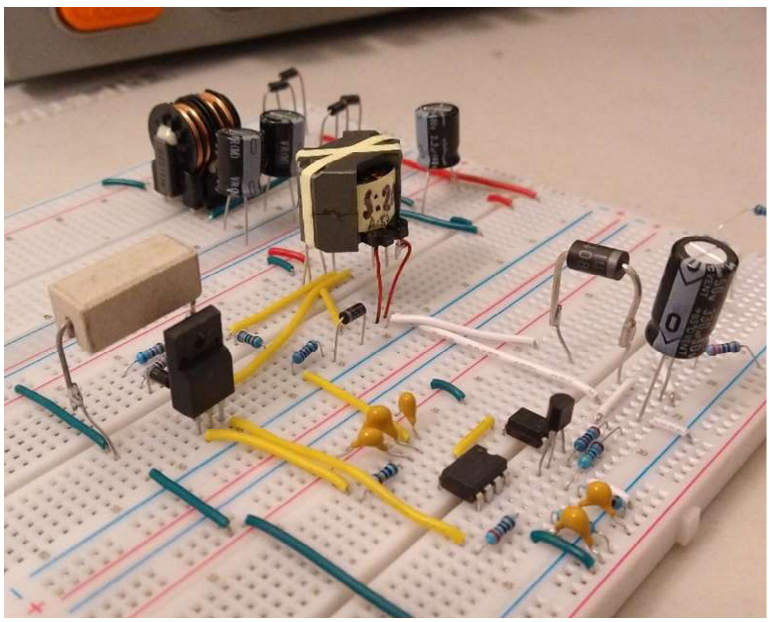

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Introduction

A switch mode power supply is one that uses a form of switch to regulate its output either by monitoring current or voltage. Switch mode power supply have superior efficiency at higher power application as opposed to linear regulator due to the completely on or off feature of the switch. Switch mode power supply consist of two stages, control stage and power stage.

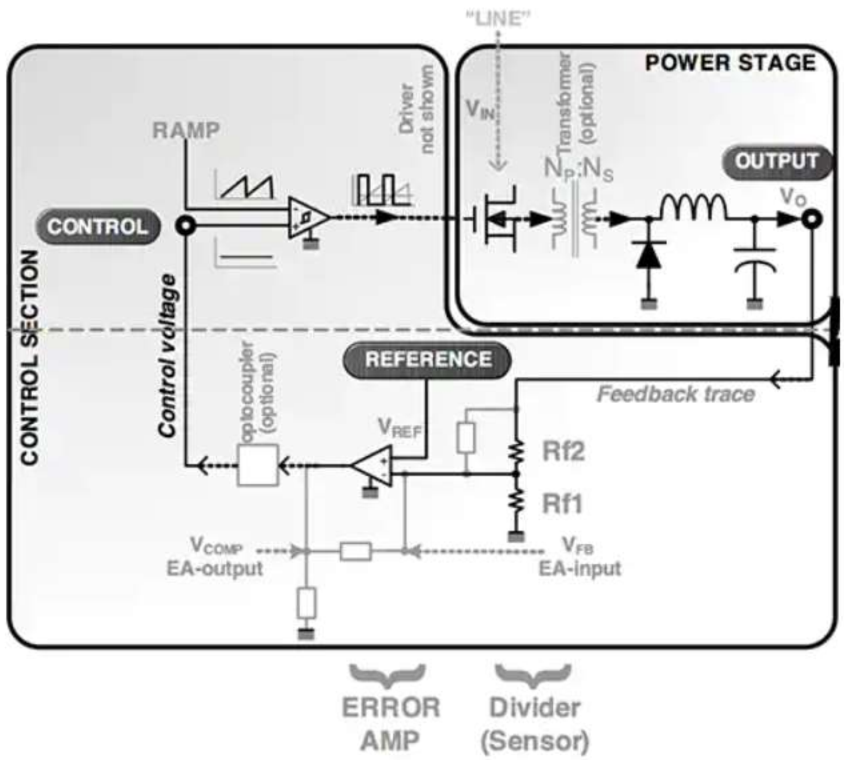


Figure 1: Stages of switch mode power supply [1, Keeping].

Shown above in Figure 1 is a typical schematic of a switch mode power supply consisting of the control and power stage. Notice that there existed a feedback path to the control IC via an optocoupler to regulate the output voltage. Optocoupler is a device that uses light to wirelessly turn on or off a photo transistor. Optocoupler is used for isolation control between the high input voltage and small output voltage side. In the case of any potential device failure this isolation will help isolate the high voltage side (control stage) from the low output voltage side (output stage where the user can potentially have contact with). Also notice a transformer is used between the power stage and the control stage. This is also used for isolation purposes and serves as a step down of the high input voltage to a lower voltage on the secondary side (output stage).

There are many converters topology available but in this project the flyback converter is used due its low parts count and easy to implement feature [2]. Though it is important to note that the flyback converter is only good for low power application typically of 10 W or less [2].

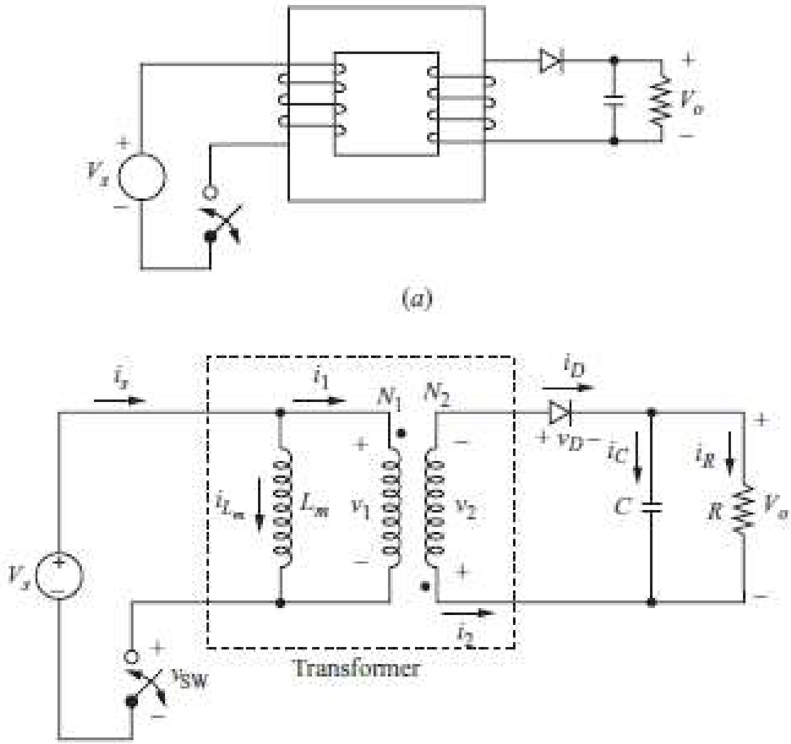


Figure 2: General flyback converter topology circuit [Hart, p. 267].

Shown in Figure 2 is a typical flyback converter circuit. For the flyback converter the energy is stored in the transformer primary winding when the switch is closed, and this energy is transferred to the secondary winding when the switch is open. It is also important to note that in Figure 2, the inductance L_m (primary winding) is a critical design parameter when designing the flyback converter [Hart, p. 266]. For more information regarding the theory behind the flyback converter please refer to the reference [Hart , p. 263-284].

Objective

Design an AC to DC switch mode power supply using the flyback topology.

Design Specifications

1. Design AC to DC switch mode power supply using the flyback topology.
2. Isolation is required between both the input and output stages.
3. Use 170 V_{dc} as input (not required). Can also use smaller input source (40 V_{dc}) for safety reasons.
4. The high frequency transformer used in the flyback converter must be custom-built. Please refer to Appendix B for detailed directions.
5. Output stage must be able to deliver 5 W to a 5 Ω load. This mean that the output must be able to maintain 5 V at 1 A with a load of 5 Ω.

Materials

1. Breadboard
2. LM5021 (current mode PWM controller for flyback and forward converter topology)
3. TL431 (programmable zener diode)
4. TF4N60 (MOSFET)
5. High frequency transformer (custom-built, refer to Appendix B for details)
6. Step down transformer (120 V_{rms} to 28 V_{rms})
7. 1N4007 (wave rectifier)
8. PC817D (Optocoupler for feedback)
9. Resistors
10. Capacitors
11. Common choke line filter
12. Oscilloscope
13. Multimeter

Procedure

1. Build the transformer following the steps presented in Appendix B.
2. Reference the figure show in Appendix A and built it onto a bread board using the materials listed above in the Material section.
3. Once the circuit is built onto a bread board. Check it **4 times** with the figure shown in Appendix A, and make sure it is connected correctly.
4. Double check the values of the resistors and capacitors once the circuit has been built.
5. Check the circuit configuration **one last time** before proceeding.
6. Use a load of 5 Ω at the output.
7. Apply power and observe the output voltage to be around 5 V.

8. Repeat step 6 and 7 for the different loads (10 Ω, 15 Ω, 25 Ω, 30 Ω, 50 Ω, 100 Ω and 360 Ω) and observe its output voltage. It should be regulated to be about 5 V.
9. Use a multimeter to measure the output voltage and output current from the output of the full wave rectifier.
10. Make power efficiency calculation based on data collected from step 6-9.

Design Method

The flyback converter was designed using the LM5021 constant current mode PWM controller IC. This design referenced the circuit generated from the TI Webench designer tool. The reference link to the LM5021 TI Webench dedicated designer tool and simulation model can be found at the reference [5]. This generated design from TI Webench designer tool was modified to use a custom-built transformer that has a primary coil (60 turns), auxiliary coil (50 turns), and secondary coil (20 turns). This custom-built transformer is shown below in Figure 3.

$$\frac{v_1}{v_2} = \frac{N_1}{N_2} \qquad \textit{Transformer turns ratio equation} \qquad \textit{Equation } 1$$

$Let\ v_1 = 40\ V, \quad then\ v_2 = 13\ V\ and\ v_a = 33\ V$

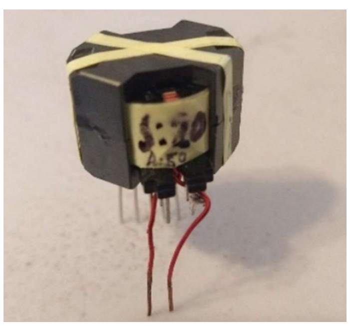


Figure 3: The custom-built transformer.

Note: *A transformer winding procedure is presented in Appendix B on how to wind this kind of transformer.*

With the transformer built, its inductance on each coil is measured and organized as shown below in Table 1

Table 1: The measured transformer coil inductance

Transformer coil	Inductance measured
Primary	12.4m
Auxiliary	8.6m
Secondary	1.3m

Note: *Appendix C provided the steps on how to measure inductance using a function generator and oscilloscope.*

The designed circuit for the flyback converter is shown below in Figure 4. Notice that this design has the input and output stages optically isolated. This mean that the input side (control stage) do not have direct contact with the output stage. Isolation between the input side and output side means that not even their ground bus is connected together. The only connection the output stage has with the input stage is through the PC817D optocoupler (wireless connection). This optocoupler provided the necessary feedback for the LM5021 IC to regulate the output voltage at the output stage without direct contact. The PC817D optocoupler has an internal LED and a photo transistor. The PC817D optocoupler with the TL431 (programmable zener diode) set the desired output voltage reference (5 V). The internal LED of the PC817D will turn on or off depending on if the zener diode is in reverse break down mode or not, and this will optically produce a signal on the other side (input stage) of the optocoupler (photo transistor) which is fed to the LM5021 IC as feedback for output voltage regulation.

The transformer also has isolation between its primary and secondary coils. This will also ensure that if any component were to fail or anything bad happened to the input stage of the flyback converter, the input stage (high voltage) will be isolated from the output stage (low voltage). This will help provide some safety for the user.

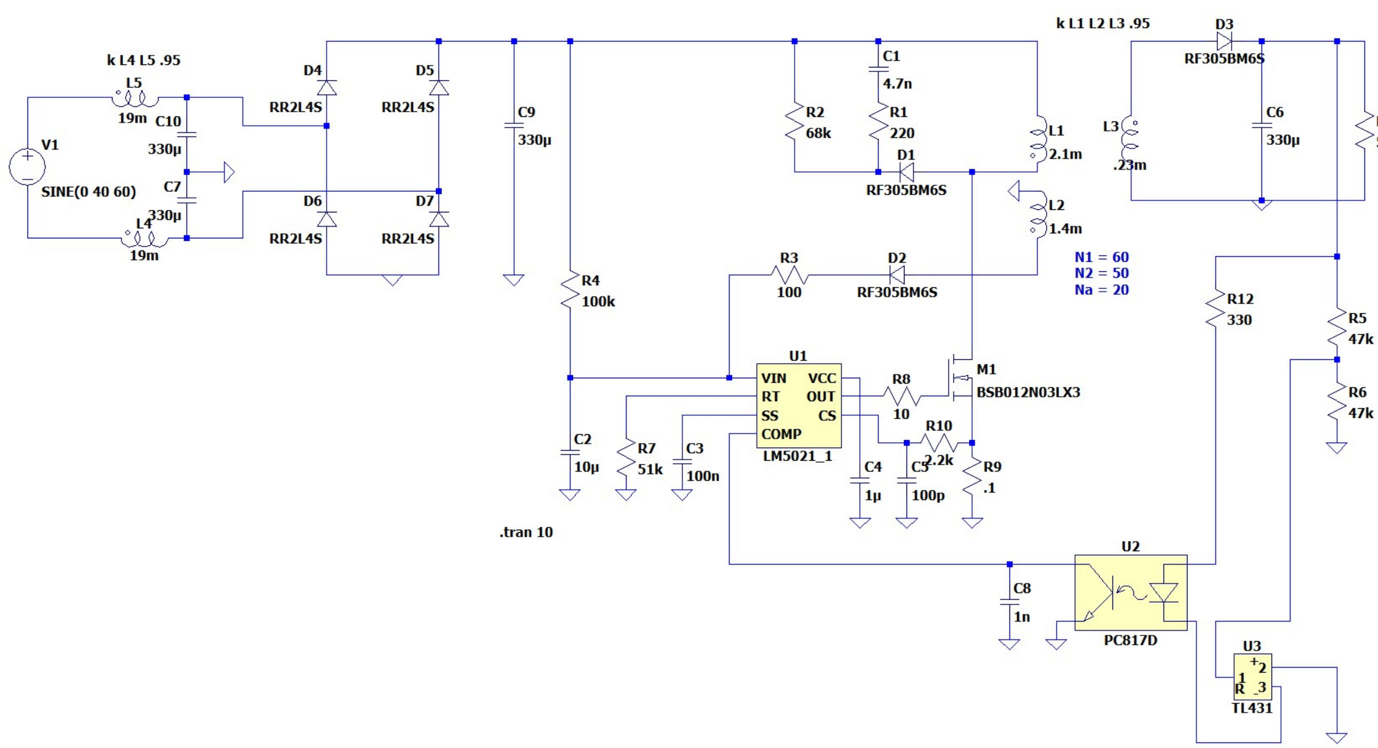


Figure 4: The designed flyback circuit.

This is the designed circuit for the optically isolated flyback converter using the LM5021 IC for regulation. The circuit built on a breadboard for testing in this project is shown below in Figure 5.

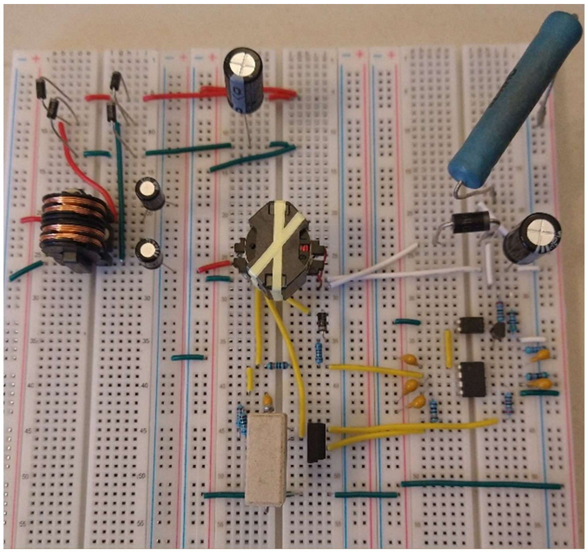


Figure 5: The flyback converter layout built on a breadboard.

Shown above in Figure 5 is the circuit of the designed flyback converter that was built onto a bread board. This is the flyback converter circuit used in this project for testing and data gathering. The results and analysis are presented below.

Results and Analysis

LTSpice Simulation Results and Analysis

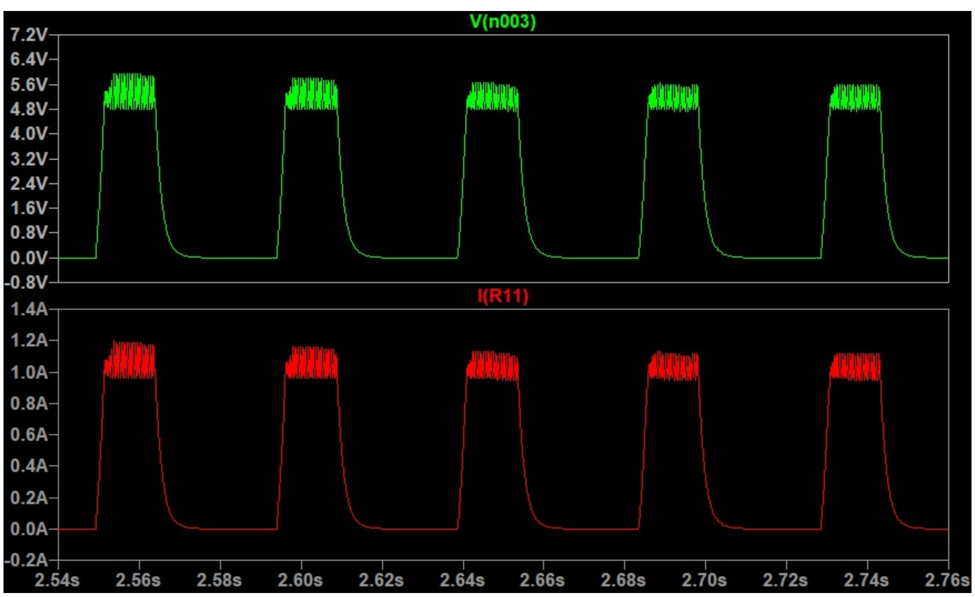


Figure 6: Simulated results.

The simulation result from LTSpice is shown in Figure 6 with a load of 5 Ω. The programmable zener diode (TL431) is programmed to have a reverse break down voltage of 5V (Appendix D provides a guide on how to program this TL431 zener diode). This implies that the output voltage will be regulated at 5 V. From Figure 6 the output voltage is about 5 V and the current through the load is about 1 A.

It is very important to notice that the output of the flyback converter do not stay at 5 V and 1 A continuously. The simulation shows that the output drops back down to 0 V after about .2 second and periodically repeat this on and off behavior. Though this behavior is not desirable.

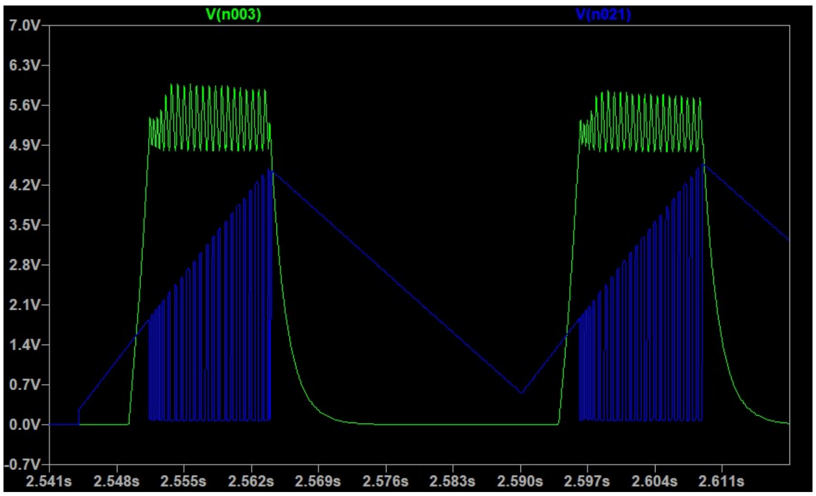


Figure 7: The feedback signal (blue signal) of the optocoupler at the control side.

Shown above in Figure 7 is the feedback signal (blue signal) of the optocoupler on the control side. Notice the optocoupler feedback signal is switching on and off only. This signal is fed back into the COMP (pin 1) of the LM5021 IC. Internally this fed back signal on COMP (pin 1) is being compared to a ramp signal generated by the current sense pin (CS pin 6) . This can be seen in the internal block diagram of the LM5021 as show below in Figure 8.

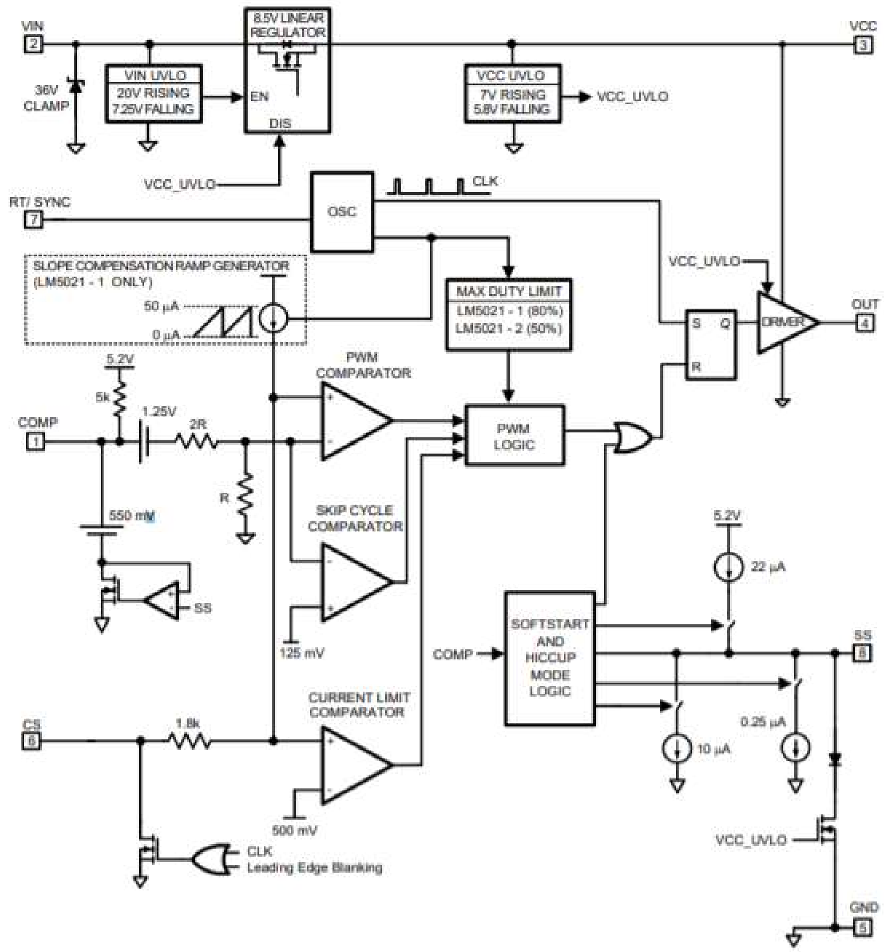


Figure 8: Internal block diagram of the current mode PWM controller LM5021 IC [3].

This kind of comparison between the output voltage and the sensed current ramp from the primary side of the transformer is compared together to determine the duty cycle of the PWM signal driving the switch.

Shown below in Figure 9 is an easier to understand diagram of this current mode PWM controller topology. This current mode PWM controller topology has two control loops, an inner loop (current ramp), and the output loop (output voltage).

The inner control loop (current ramp) is used to sense the current through the primary inductor in conjunction to the output voltage control loop to produce a better and faster response to changes in input voltage or output voltage [Keeping]. Since the current in the primary coil rise with a slope determined by the difference between the input and output voltages, this inner control loop (current ramp) help provide better response to changes in input voltage or output voltage as opposed to just using the voltage feedback loop (outer loop) [Keeping].

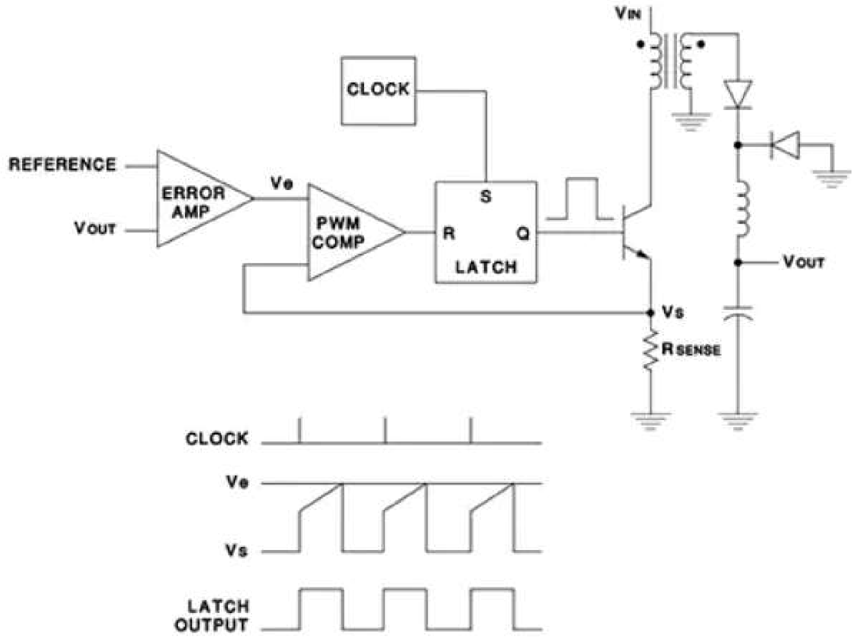


Figure 9: Current mode switch regulator [Keeping].

Shown in Figure 9 is the two-control loop. Notice the inner control loop (current ramp) is on the input stage, while the outer control loop (voltage feedback) is on the output stage. For isolation purposes the outer loop (voltage feedback) is typically implemented by using an optocoupler. And so due to the current sensing control loop of the LM5021 it is categorized as a current mode PWM controller IC.

Experimental Results and Analysis

In this section the hand-on experimental results will be presented and analyzed.

Figure 10: Output voltage waveform when the load is 5 Ω.

When the load is 5 Ω the output voltage has an average value of 4.82 V as shown in Figure 10. Notice there is a lot of voltage spikes at the output, but it never goes below zero. Also, the spikes only go toward 0 V and not upward in amplitude.

Since the load is 5 Ω and the average output voltage is 4.82 V, this mean the output power is 4.64 W. This input power is measured to be 10.21 W. The efficiency of this flyback converter with a load of 5 Ω at 4.82 V is then 45.47%.

Figure 11: Output voltage ripple measurement when the load is 5 Ω.

In Figure 11 shows the zoomed in image of the output voltage waveform when the load is 5 Ω. This waveform has a characteristic of a ripple, but it is not. This triangular like ripple is produced due to the optocoupler. The optocoupler is producing an on and off signal and this signal is optically fed back to LM5021 for comparison to regulate the desired 5 V output. Therefore, due to this behavior of the optocoupler the waveform in Figure 11 has this triangular wave like ripple. This on off behavior is measured to have a ripple of .7 V.

Figure 12: Output voltage waveform when the load is 10 Ω.

When the load is 10 Ω the output voltage is maintained at 4.93 V. This output voltage waveform is shown in Figure 12 above. This prove that the LM5021 is regulating the output voltage properly since the load is changed and the output voltage is still maintained (close to 5 V).

The output power of this flyback converter when the load is 10 Ω is 2.43 W. The input power is measured to be 5.9 W. Therefore, the efficiency is 41.1% when the load is 10 Ω and output voltage is 4.93 V.

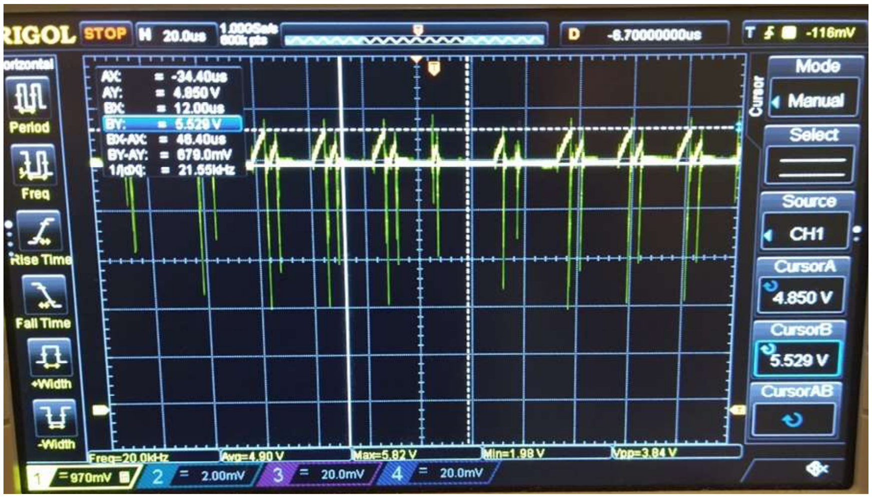


Figure 13: Output voltage ripple measurement when the load is 10 Ω.

Shown above in Figure 13 is the on off ripple at the output when the load is changed to 10 Ω. This on off ripple is measured to be .679 V.

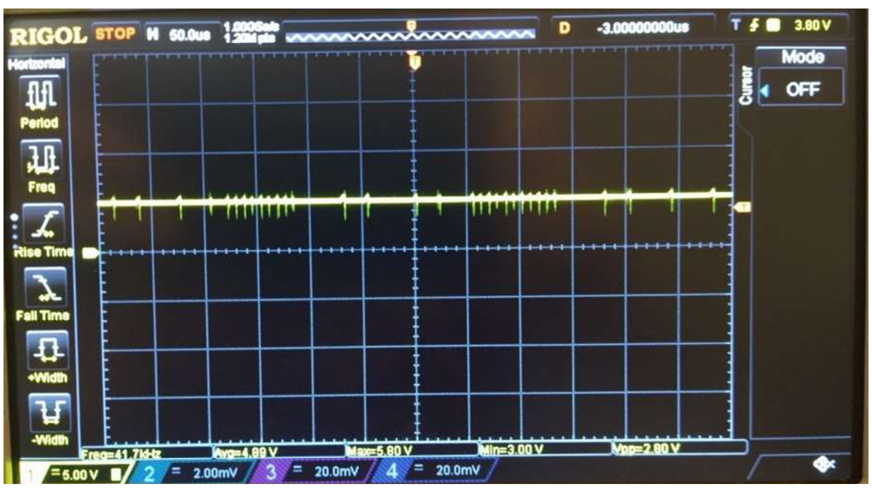


Figure 14: Output voltage waveform when the load is 30 Ω.

The output voltage waveform for a 30 Ω load is shown in Figure 14 above. The average voltage is maintained at 4.89 V. It can be observed that as the load gets bigger in value, the output voltage gets closer to the desired 5 V.

The input power for when the load is 30 Ω with output voltage of 4.89 V is measured to be 2.92 W. The output power is V^2/R, which calculates to be .797 W. This mean the efficiency of this flyback converter is 27.2% when the load is 30 Ω and output voltage is 4.89 V.

Figure 15: Output voltage ripple measurement when the load is 30 Ω.

The on off ripple at the output when the load is 30 Ω is shown in Figure 15 above. This on off ripple is measured to be .44 V. It can be concluded that as the load gets bigger and bigger, the amplitude of the on off ripple behavior at the output is less in value.

Below in Table 2 summarized all the experimental data collected for different loads

Table 2: Load efficiency measurements

Load [Ω]	V_{in} [V_{rms}]	I_{in} [A]	P_{in} [W]	V_{out} [V]	I_{out} [A]	P_{out} [W]	Efficiency [%]
5	34.4	0.297	10.2168	4.82	0.964	4.64648	45.47882
10	34.76	0.17	5.9092	4.93	0.493	2.43049	41.13061
15	35.9	0.111	3.9849	4.9	0.326667	1.600667	40.1683
25	36.5	0.09	3.285	5.01	0.2004	1.004004	30.56329
30	36.54	0.08	2.9232	4.89	0.163	0.79707	27.26704
50	36.92	0.044	1.62448	5.03	0.1006	0.506018	31.14954
100	37.18	0.023	0.85514	5.1	0.051	0.2601	30.41607
220	37.58	0.012	0.45096	5.1	0.023182	0.118227	26.2168
360	37.58	0.008	0.30064	5.1	0.014167	0.07225	24.03206

In this project the designed flyback converter was tested with different loads. For the different loads the output voltage not exactly 5 V but close enough to 5 V. The power efficiency for these different loads is organized and show above in Table 2. The power efficiency waveform for this flyback converter is generated from the data of Table 2 and is shown below in Figure 16.

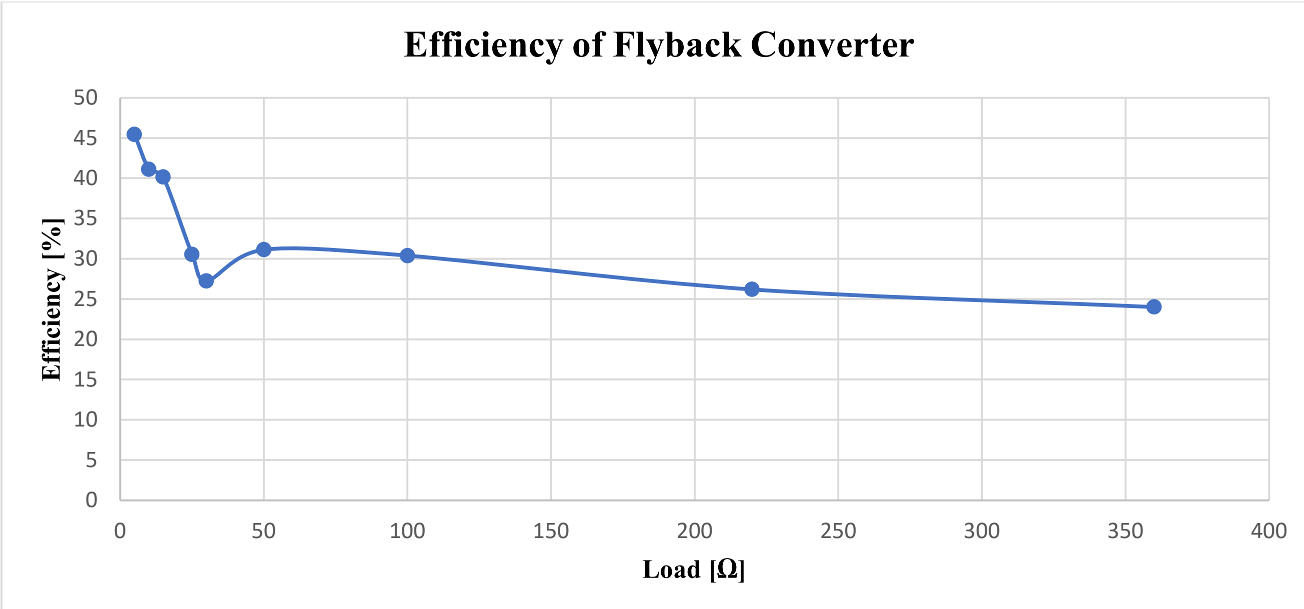


Figure 16: Flyback converter efficiency measurement for different loads.

When the load is plotted with respect to its efficiency the waveform is as shown in Figure 16. From Figure 16 it can be visually observed that as the load increased in value the efficiency drops. From the waveform of Figure 16 it can be concluded that this flyback converter has the best efficiency when the load is 5 Ω when compared to all the other tested loads, even though the efficiency at 5 Ω is only 45.4% as all the other efficiency are less than 45.4%.

There is also a dramatic efficiency drop when the load is 25 Ω and 30 Ω. And when the load is 50 Ω the efficiency slightly increases and then continue to decrease as the load value is increased.

Discussion

In this project an AC to DC flyback converter was designed using the LM5021 current mode PWM controller IC. The circuit built around the LM5021 was generated using the TI Webench dedicated software for the LM5021 [5]. The generated circuit from TI Webench was modified to meet the specification of this project. The flyback converter is used due to its isolation feature and low parts count. One of the original design specifications of the flyback converter was to have an input voltage of 170 V_{dc} but due to safety reason this design parameter was changed. The change is to use a transformer to step the 170 V_{dc} (from the wall output) down to 40 V_{dc}. Other than this, the overall design specifications remain the same. The flyback converter must use a custom-built high frequency transformer, have complete isolation between input and output stage, and be able to drive a 5 Ω load at 5 W. This mean with a 5 Ω load the flyback converter must be able to deliver 1 A of current.

It is also important to note that the simulated output voltage did not exactly match the experimental results. As the simulation predicted that the output would maintain 5 V at 1 A for a

5 Ω load for a certain amount of time and would drop down to zero, and this behavior will repeat periodically. Though the experimental results didn't reproduce this behavior. From the waveform gathered from the experiment as shown previously in Figure 10, 11, 12, 13, 14, and 15 the LM5021 produced a behavior that can be described an on off ripple behavior. This on off ripple behavior is caused by the feedback of the optocoupler. Since the optocoupler is producing an on off feedback signal to the LM5021 IC for output voltage regulation, therefore the LM5021 is turning on and turning off its switching control at times to maintain the desired 5 V.

From experimentation it is very important to have a large enough capacitor at the output of the rectifier bridge. If a small capacitor is used, the RC constant is too small and the capacitor will not be able to hold the output voltage long enough for the LM5021 to function properly as it is powered by the auxiliary winding of the transformer. For example, when a 2.2 uF capacitor is used at the output of the bridge the LM5021 undergo an on off behavior and cannot be on long enough to truly sustain itself. This will force the LM5021 IC to turn off and on continuously and the 5 V output voltage cannot not be maintained. Such behavior can also be simulated and observe as shown below in Figure 17. Therefore, the capacitor at the output of the rectifier bridge must be selected to be large enough, in this case a 330 uF capacitor is used for proper operation of the LM5021 IC.

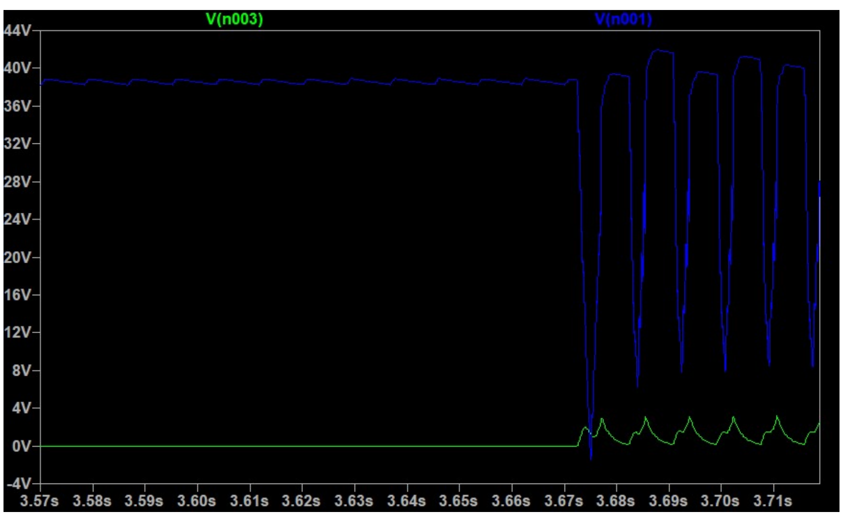


Figure 17: On and off behavior is observed in simulation and experiment.

Something that should also be mentioned is that for smaller load (example 5 Ω) the designed flyback converter can maintain the output voltage to (about 5 V), but the flyback converter produces a squeaking sound that can be heard by the ear. This sound seems to be originated from the custom-built transformer.

The 5 V output voltage of the flyback converter was tested with loads and its efficiency is recorded and shown above in Table 2 and Figure 16. It can be concluded that as the load is increased in value (flyback converter operating in low power mode) the efficiency decreases. This implies that the flyback converter has the best efficiency performance when the load is smallest (5 Ω). The power efficiency for a load of 5 Ω is 45.4%. This efficiency is not as good when compared to ready to use commercial flyback converter, but the 45.4% is the best performance out of all the data set collected.

Overall, the design specifications have been met as the out of the flyback convert was able to maintain a voltage of 4.82 V when the load is 5 Ω producing an output power of 4.6 W. Even though it is not exactly 5 W it is close enough to the 5 W specification.

Conclusion

In this project an AC to DC flyback converter was designed and implemented using the LM5021 constant current PWM controller IC. The designed flyback converter has full isolation between the input and output stages due to its usage of a custom-built high frequency transformer and feedback through an optocoupler. The designed flyback converter can output 4.6 W to a load of 5 Ω with efficiency of 45.4%. Therefore, the flyback converter has been successfully designed and tested and has met all design specifications.

Future Work

In future continuation work with the flyback converter, it will have an input power directly from a wall outlet with voltage of 170 V_{rms}. This mean that the high frequency transformer will need to be redesign with proper turn ratios. The building of the transformer will also be further explored to help eliminate the squeaking noise it produces. A better efficiency percentage will also be a good target, as in this project a efficiency of only 45.4% was achievable.

The forward converter could also be explored as the inductance of the transformer is not a design parameter, though it does require more components. Some information regarding the forward converter is that it is an isolated converter and can be seen in Figure 18 below. Forward converters are considered low to medium power converter as it can supply up to 500 W, though the disadvantage is that it has high voltage stress across its switching transistor [2, p.299].

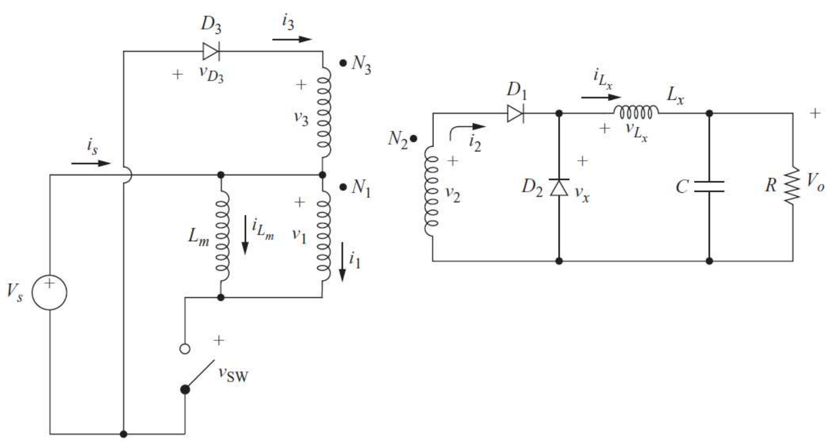
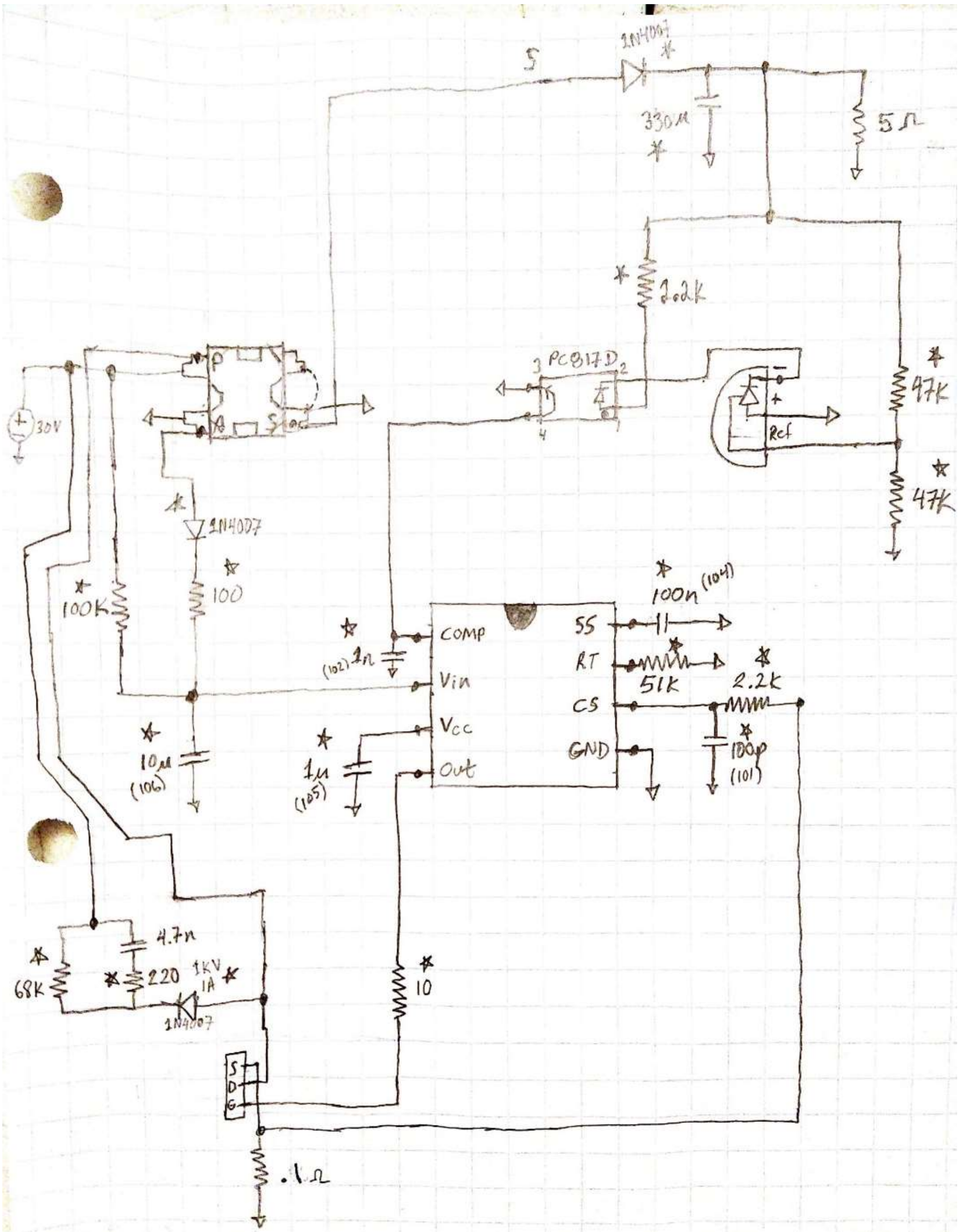


Figure 18: Forward converter circuit topology [2, page 277].

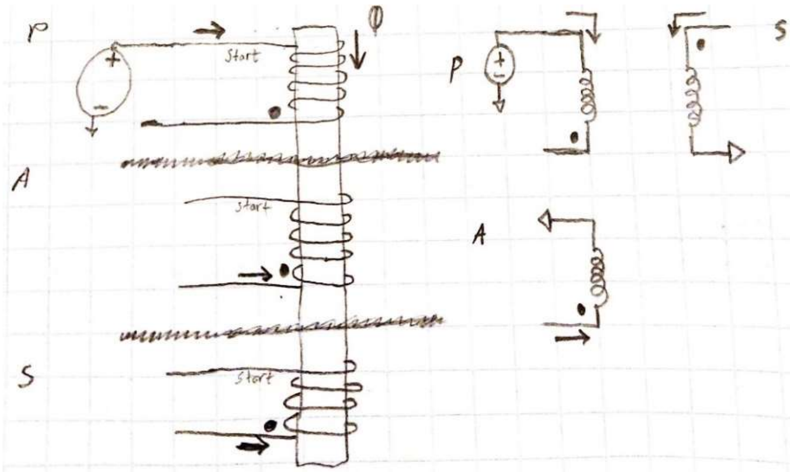
Appendix A

Component Layout and Connectivity Schematic



Appendix B

Transformer design tutorial

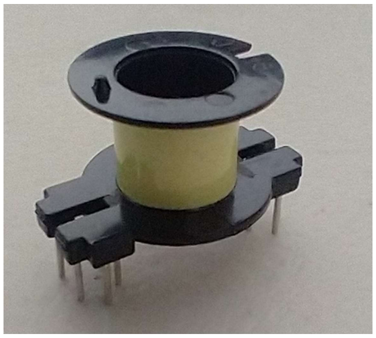


We will be building a high frequency transformer in this section. The above figure is what our design will follow. The right-hand rule is an important concept in using to determine the direction of current flow, which help determine where to put the dot on which side of each coil.

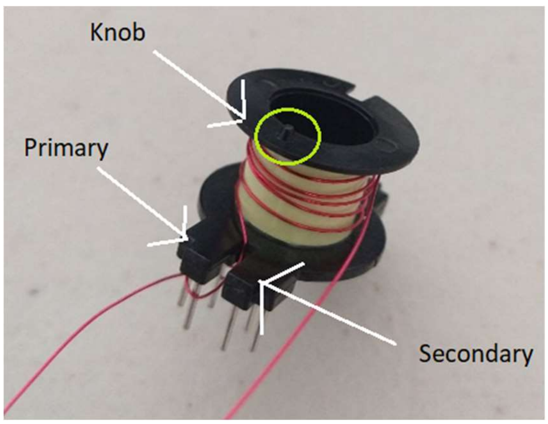
Build the transformer following the steps below:

Step 1: Gather the following equipment shown below. Note that we are using two different wire size (30 AWG and 28 AWG). The 30 AWG is for primary winding, and the 28 AWG is for the auxiliary and secondary winding. The tape we are using called yellow polyester film tape. You can order the following item from the links provided in the Link to Purchase section of this document.

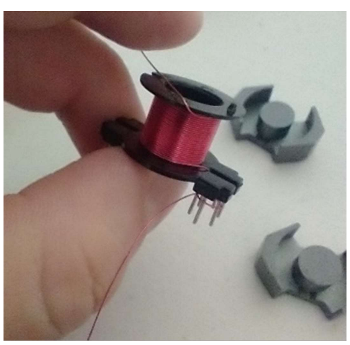
Step 3: Start by putting an isolation layer of yellow tape on the transformer bobbin.



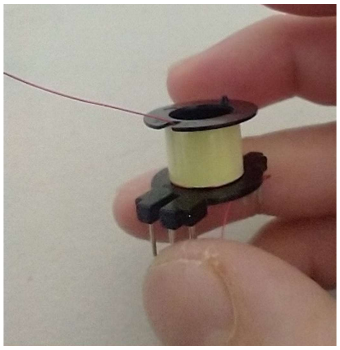
Step 4: Use the side with the little knob as the primary side. Use the 30 AWG wire and start to wind in a clockwise direction around the bobbin. Make sure that each turn is tightly winded around the bobbin. Make 30 clockwise turn.



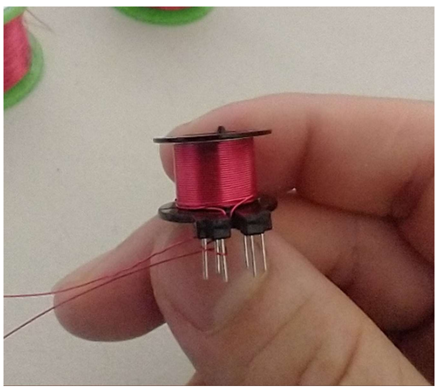
Step 5: Notice that the winding is neatly winded around the bobbin and not overlapping. This shows the 30 clockwise turns.



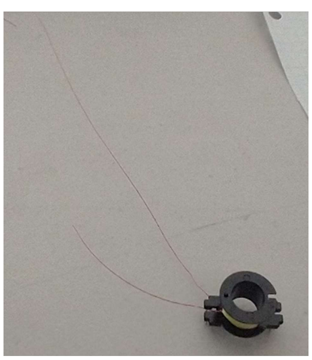
Step 6: Add a layer of yellow tape on top of the first layer (30 turns). This will add isolation between the next layer (still is for primary side). After adding layer of tape, continue to make another 30 clockwise turns.



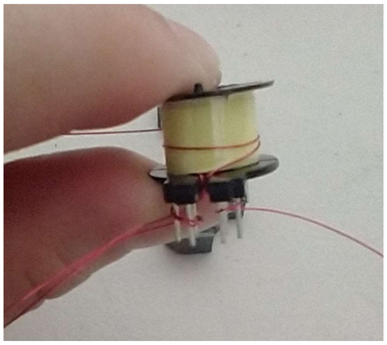
Step 7: Here show the final winding of the primary side. Notice the start and ending of the windings is put to the left at the bottom of the bobbin. Then add a layer of yellow tape for isolation before continuing to the next step.



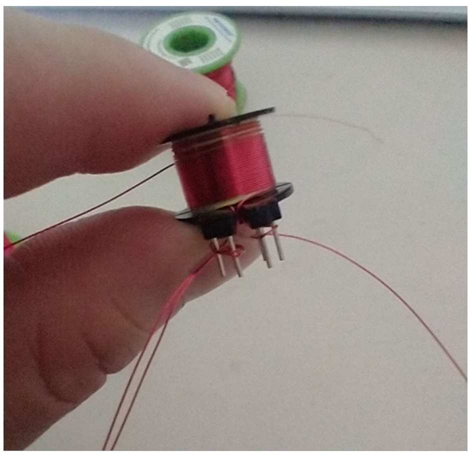
Step 8: Now that the winding of the primary coil is finished, cut the wire off each end. Make sure to have the **ending end cut shorter than the starting end**. So that we will know which wire is the starting and which is the ending.



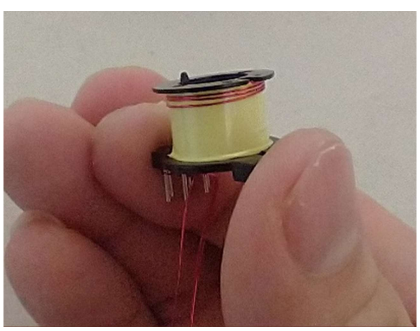
Step 9: Now we are going to wind the auxiliary. We will be using the 30 AWG. We will still reference the little knob side of the bobbin. Then start winding 25 turns in a **counterclockwise** direction around the bobbin. Remember try not to overlap each turn and make each turn as tight and close to each other as possible. Also note that we are putting the starting wire of the auxiliary to the bottom right side of the bobbin with the knob.



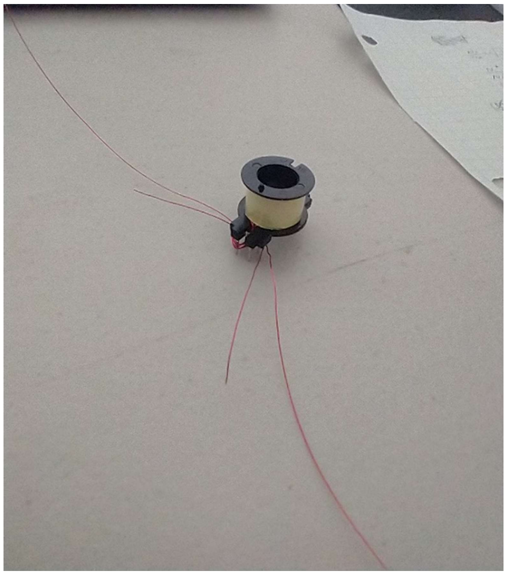
Step 10: Here show the first 25 turns of the auxiliary side. Now add another layer to yellow tap on top of these 25 turns.



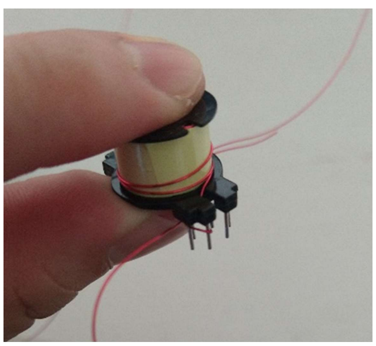
Step 11: After adding the layer of tape, then continue to make another 25 turns **counterclockwise** (remember this is still for the auxiliary side).



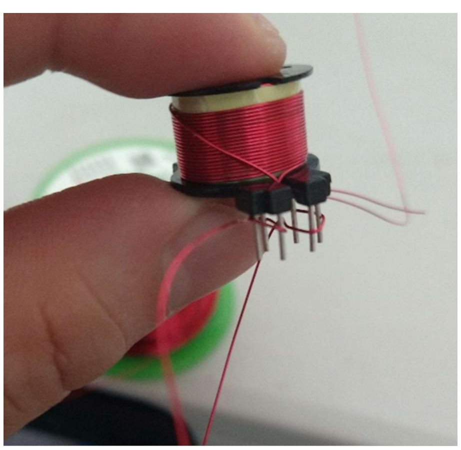
Step 12: Once the last 25 turns is finished, then add a layer of tape on top of this layer too. Remember to **cut the ending end such that it has a shorter length then the starting end**. We can see this as shown below.



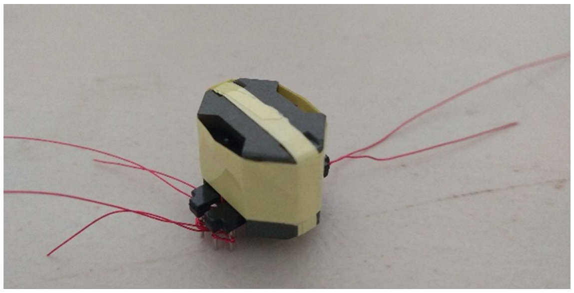
Step 13: In this step we will wind the secondary side of the transformer. We need to use the side of the bobbin that have a **notch at the top**. We will use the 28 AWG wire. Start by attaching the starting wire to the bottom left pin of the bobbin. Then make 20 **counterclockwise** turns.



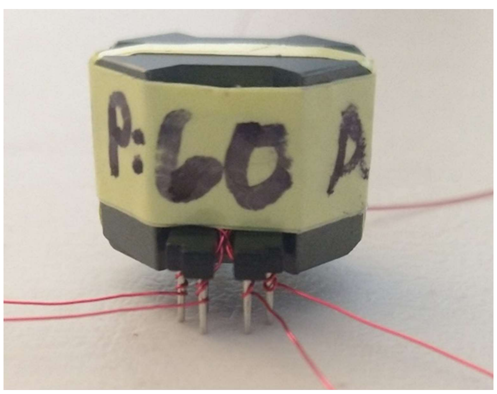
Step 14: Once the 20 counterclockwise turn is completed, then add a layer of yellow tape to the primary winding. Again, remember to **cut the ending end such that it has a shorter length then the starting end**.



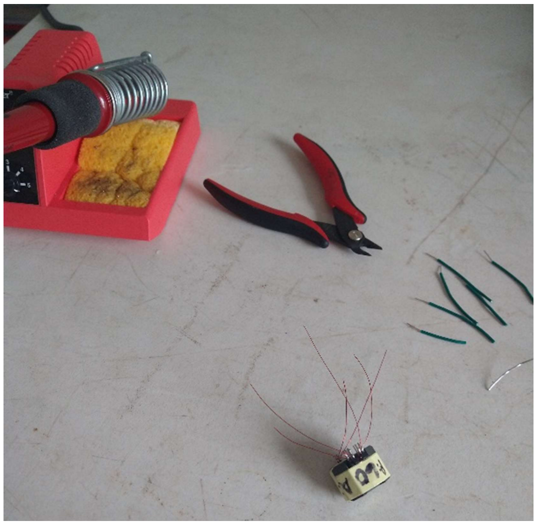
Step 15: Put the ferrite core onto the bobbin as shown below. Then add taps to secure the ferrite core in place. Don't glue the ferrite core in case later we need to reuse the transformer again, so it will be easier to take it apart without damaging it.



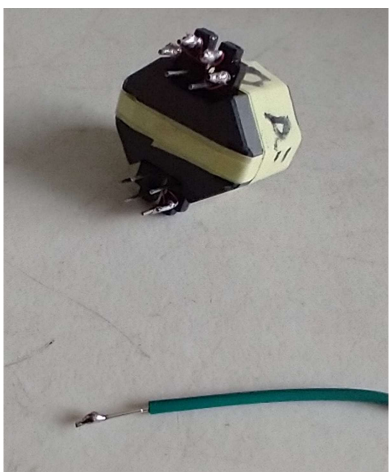
Step 16: Add labeling to the transformer as shown below. This will help us know what the transformer turn ratio is in case we don't remember later. Show below is the primary and auxiliary side. Notice that the starting end of each coil (primary and auxiliary) is attached to the **inner pin** by winding it around the pin. The ending end of each coil (primary and auxiliary) is attached to the **outer pin**. It is very important that you follow this same protocol for the secondary side too.



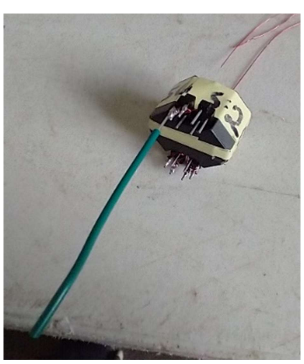
Step 17: In this step we will solder the start and end of each coil onto each bottom pin of the bobbin.



Step 18: Here the start and ending side of each coil is soldered to the selected bottom pins. Now add a little bit of solder to a noncoated 22 AWG wire as show below. We will solder this onto each used pin so that we can use the transformer on a breadboard.



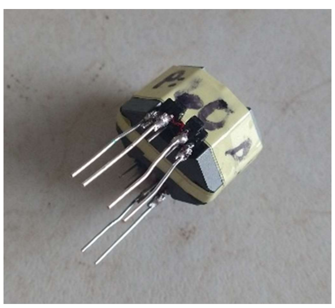
Step 19: Show below is the extension soldered onto one of the bottom pins of the bobbin. Again, we are doing this so that we can use the transformer on a breadboard.



Step 20: Once each selected bottom pins have a leg extension added, use a multimeter that have short detection capability to ensure that the start and end of each coil have a short connection. This means the multimeter will beep if you connect the start and end of each coil onto the multimeter. This test will ensure that each coils have a connection from the start to the end.

In the case of no beep is heard when connecting the multimeter to the start and end of a coil, this mean that there is no connection of the coil being tested. Therefore, you **MUST** undo the windings and start over again.

Step 21: Now you are almost done. All you need to do now is to measure the inductance of each coil. Go to Appendix C for detailed direction on how to measure inductance using a function generator and an oscilloscope.



Appendix C

How to measure inductance of a coil

Note: *Reference to this procedure is listed as [4] in the reference section*

Method

We will be using a function generator (capable of sine wave generation) and an oscilloscope to measure an unknown inductance.

Materials

1. Function generator
2. Oscilloscope
3. Resistor (150 Ohm, just have to be small enough. All we need is a known resistor)
4. An inductor (to be measured. So, it will be nice if this inductor's value is known so we can confirm after measurement and see how accurate our measurement really is. *But it is not required to have a known inductor*.)
5. Multimeter (to measure the resistance of the resistor we are using ~150 Ohm)

$$R_0 = R_L\left(\frac{v_o}{v_L} - 1\right)\ [\Omega] \qquad\qquad Equation\ 1$$

$$L = \sqrt{\frac{1}{3} * \left(\frac{R_0}{2\pi f}\right)}\ [H] \qquad\qquad Equation\ 2$$

Procedure

1. We must first know the output impedance of the function generator.
   a) Tune the function generator to output a sine wave with 5 V_{pp} and average at 0 V with frequency of 10 kHz.
   b) Connect the oscilloscope to the output of the function generator to confirm this. Note down this V_{pp} as V_o .
   c) Use the multimeter to measure the actual resistance of the 150 Ohm resistor. Take note of this value as R_L .
   d) Connect the resistor in series with the function generator. Observe the amplitude drop from the oscilloscope screen. Record this V_{pp} as V_L .
   e) Use equation 1 and calculate the R_o value (output impedance of the function generator).
2. We will now measure the inductance of the inductor.
   a) Connect the inductor in series with the function generator by replacing the inductor with the resistor.
   b) Observe the V_{pp} across the inductor on the oscilloscope. Decrease or increase the frequency such that the V_{pp} across the inductor is half of 5 V_{pp}. This mean the

frequency should be decrease or increase until the voltage across the inductor is 2.5 V_{pp}.

c) Once the V_{pp} is dropped down to 2.5 V_{pp} by decreasing or increasing the frequency of the function generator. Please note down on this frequency (call it f) at which the voltage across the inductor is 2.5 V_{pp}.
d) Use equation 2 to calculate the inductor value. *Note that R_o was calculated earlier in step 1e already.*
e) Compare this calculated inductance to the known inductance value (assuming it is a known inductor) Otherwise, it is fine if it is not known beforehand. Just believe in yourself and know that this calculated inductance is the inductor's inductance.
f) Now you know how to calculate inductor value.
g) See you next time!!!

Appendix D

How to program the LT432 zener diode

In this section how the LT431 is programmed will be discussed with reference to its datasheet.

From the datasheet of the TL431 of page 25 (shown below in Figure D2) it shows a shunt regulator schematic. It consists of 1 voltage divider network (R1 and R2). The output voltage is given as:

$$v_0 = \left(1 + \frac{R_1}{R2}\right) v_{ref} \qquad\qquad Equation\ \ D1$$

Therefore, to program the reverse breakdown voltage of the zener diode to be 5 V, R1 and R2 must be chosen properly. Note that the V_{ref} is unknown at this point from Equation D1. Further looking at the datasheet of page 6 (as shown below in Figure D1) the typical V_{ref} value is 2.495 V. By looking through the datasheet V_{ref} is now known.

It must be noted that the bias current to the zener diode cathode terminal must not exceed 150 mA. It is recommended by the datasheet on page 5 (shown below in Figure D3) to have a bias current bigger than 1 mA but less than 100 mA.

$$Now\ let\ R1 = R2 = 47k$$

$$then\ \ v_0 = \left(1 + \frac{47k}{47k}\right) 2.495 = 4.99\ V$$

Therefore, with this calculation for the value of R1 and R2 the zener diode is programmed to have a reverse break down voltage of 4.99 V.

10.2.2 Shunt Regulator/Reference

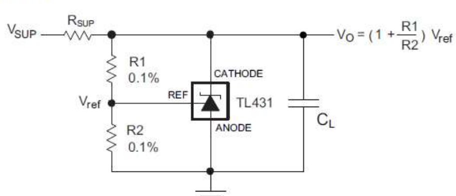


Figure 27. Shunt Regulator Schematic

10.2.2.1 Design Requirements

For this design example, use the parameters listed in Table 1 as the input parameters.

Table 2. Design Parameters

DESIGN PARAMETER	EXAMPLE VALUE
Reference Initial Accuracy	1.0 %
Supply Voltage	24 V
Cathode Current (Ik)	5 mA
Output Voltage Level	2.5 V - 36 V
Load Capacitance	100 nF
Feedback Resistor Values and Accuracy (R1 & R2)	10 kΩ

Figure D2: Shunt regulator design (datasheet p. 25).

7.4 Recommended Operating Conditions

See(1)

			MIN	MAX	UNIT
V_{KA}	Cathode voltage		V_{ref}	36	V
I_{KA}	Cathode current		1	100	mA
T_A	Operating free-air temperature	TL43xxC	0	70	°C
		TL43xxI	–40	85	
		TL43xxQ	–40	125	

Figure D3: Absolute maximum rating (datasheet p.5).

7.5 Electrical Characteristics, TL431C, TL432C

over recommended operating conditions, T_A = 25°C (unless otherwise noted)

PARAMETER		TEST CIRCUIT	TEST CONDITIONS		TL431C, TL432C			UNIT
					MIN	TYP	MAX	
V_{ref}	Reference voltage	See Figure 20	$V_{KA} = V_{ref}$, I_{KA} = 10 mA		2440	2495	2550	mV
$V_{I(dev)}$	Deviation of reference input voltage over full temperature range(1)	See Figure 20	$V_{KA} = V_{ref}$, I_{KA} = 10 mA,	SOT23-3 and TL432 devices		6	16	mV
				All other devices		4	25	
ΔV_{ref} / ΔV_{KA}	Ratio of change in reference voltage to the change in cathode voltage	See Figure 21	I_{KA} = 10 mA	ΔV_{KA} = 10 V – V_{ref}		–1.4	–2.7	mV/V
				ΔV_{KA} = 36 V – 10 V		–1	–2	
I_{ref}	Reference input current	See Figure 21	I_{KA} = 10 mA, R1 = 10 kΩ, R2 = ∞			2	4	μA
$I_{I(dev)}$	Deviation of reference input current over full temperature range(1)	See Figure 21	I_{KA} = 10 mA, R1 = 10 kΩ, R2 = ∞			0.4	1.2	μA
I_{min}	Minimum cathode current for regulation	See Figure 20	$V_{KA} = V_{ref}$			0.4	1	mA
I_{off}	Off-state cathode current	See Figure 22	V_{KA} = 36 V, V_{ref} = 0			0.1	1	μA
$\|z_{KA}\|$	Dynamic impedance(2)	See Figure 20	$V_{KA} = V_{ref}$, f ≤ 1 kHz, I_{KA} = 1 mA to 100 mA			0.2	0.5	Ω

Figure D1: LT431 electrical characteristics (datasheet p.6).

Links to purchase

Bobbin and ferrite core

https://www.amazon.com/uxcell-Transformer-Bobbin-Ferrite-Vertical/dp/B07X74LYGY?pd_rd_w=5gMwP&pf_rd_p=ee521540-07c2-4687-9605-13c98e32ab2c&pf_rd_r=2C3NY2H7V7EJP2Z82K9M&pd_rd_r=846de2ce-0bee-4a1e-86c7-d8df1ce3f346&pd_rd_wg=RmcXh&pd_rd_i=B07X74LYGY&psc=1&ref_=pd_bap_d_rp_1_i

Yellow polyester film tape

https://www.amazon.com/dp/B00MWY8L3K?psc=1&ref=ppx_yo2_dt_b_product_details

Coated wires

28 AWG

https://www.amazon.com/dp/B07DYF53ZN?psc=1&ref=ppx_yo2_dt_b_product_details

30 AWG

https://www.amazon.com/dp/B07GBMKMKY?psc=1&ref=ppx_yo2_dt_b_product_details

TL431 (programmable zener diode)

https://www.amazon.com/dp/B083ZT7PFX?psc=1&ref=ppx_yo2_dt_b_product_details

Breadboard (good one)

https://www.amazon.com/dp/B07DL13RZH?psc=1&ref=ppx_yo2_dt_b_product_details

Reference

[1] Keeping, Steven. "Voltage- and Current-Mode Control for PWM Signal Generation in DC-to-DC Switching Regulators." *DigitKey*, Electronic Products, 1 Oct. 2014,

https://www.digikey.com/en/articles/voltage-and-current-mode-control-for-pwm-signal-generation-in-dc-to-dc-switching-regulators

[2] Hart, Daniel W. "DC Power Supplies ." *Power Electronics*, McGraw-Hill , 2011, pp. 265–326.

[3] https://www.ti.com/lit/ds/symlink/lm5021.pdf?ts=1641642685613

[4] https://www.youtube.com/watch?v=iQQe8uSZ8xc&list=WL&index=269&t=298s

[5] https://www.ti.com/product/LM5021