Ege Aydın
21803573

EEE313 Course Project: High Voltage Generator

Introduction

Many commercially available appliances today use very small silicone ICs which works with at very low voltages to minimize the power usage and mainly because chips would breakdown and burn under high voltages. However, this doesn't mean high voltages don't have a use case. For example, electroluminescence materials require high voltage AC in order to light. Geiger counters and vacuum tubes use high voltage to operate. There are many physics experiments that require high voltages as well. One way to easily generate high voltages is to use a step-up transformer connected to mains AC voltage. However, in that case, controlling the output voltage would be very hard. Also, if the device is known to draw very little current it may be better to limit the input current to prevent the damage in case a short circuit occurs. A device that requires a low voltage input and outputs a high voltage that depends on the input would be perfect to use in these applications. If there were also some safety precautions, it would make a great device to use in various projects.

Basic Circuit Design

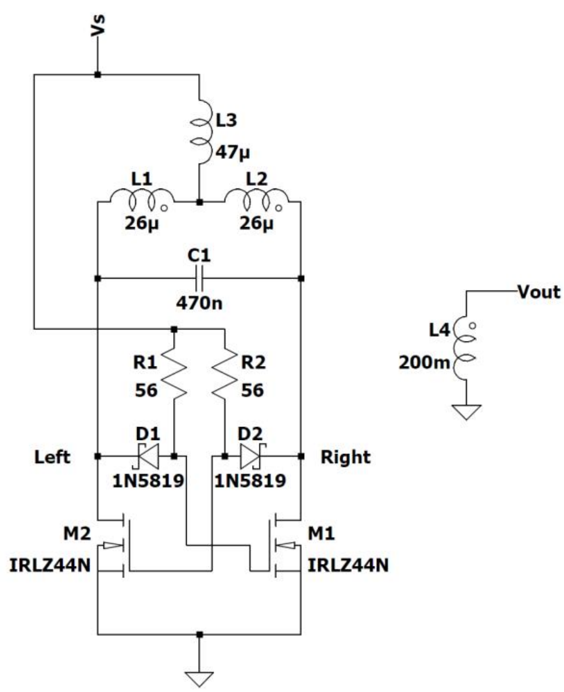

Figure 1. ZVS Circuit

The circuit given in the figure 1 is a ZVS circuit which stands for "Zero Voltage Switching". It basically energizes the LC circuit that is formed by L1-L2 and C1. Inductors L1-L2 form the primary inductor of a high voltage transformer. Since the primary has a center tap, it is shown with two equal inductors on the schematic. The transformer is wound by hand with 5 turns of primary and many turns of secondary. Assume the LC circuit is oscillating, when left increases, right side decreases. D2 starts conducting when right side voltage is low enough, which decreases gate voltage of the M2 and turns it off. In contrast, D1 is off and R1 pulls the gate of the M1 high. When a mosfet is on, drain is pulled to ground and current passes through the side the Mosfet is. This injects energy to the LC circuit and prevents the oscillation from dampening. This switching of the Mosfets ideally happen exactly when the sinusoidal oscillation passes the zero voltage. However, since the diodes have some forward voltage, they don't exactly switch at zero, but at $\pm V_{fwd}$ of the diodes. As the switching voltage gets away from zero, the efficiency of the circuit also decreases. This is because energy injection time decreases and total injected energy decreases as well. To maximize the efficiency, Schottky diodes are used which have low voltage drop and a very fast switching action.

The resonance enables the circuit to work at higher voltages than the input voltage. This is because energy gets injected while LC is in resonance so the drain voltages increase until the injected voltage is equal to losses. For example, 4V input voltage generate 10V peak drain voltage. This 10V is then increased to 400V over the transformer. The inductor L3 is a choke to separate input voltage from the AC oscillation.

The drain voltage waveforms are half sinewave for each mosfet that are 180 degrees apart. The gate voltage follows the drain as long as its diode is off. When the diode turns on the gate voltage becomes equal to V_S. Since $V_{GS} = V_{DS}$ for $V_{DS} > V_S > V_{TN}$, the mosfet gets in saturation region when the half sine wave increases over the threshold voltage of the mosfet. In saturation region, until the gate voltage gets capped at supply voltage, the current follows the drain voltage since $I_D = K_N(V_{DS} - V_{TN})^2$ and when capped $I_D = K_N\left(V_{supply} - V_{TN}\right)^2$ which is a constant value.

Adjustments and Improvements to the Circuit

One fundamental flaw of this circuit is that it requires oscillation to exist before being able to work. The circuit creates this oscillation when the power supply is connected and the voltage supply acts as a step input. But if the input voltage is not high enough or it is applied gradually, it won't be enough to start the oscillation. When the oscillation does not start, one of the Mosfets stuck in the SAT mode and does not turn off. Only thing between the drain of the Mosfets and power supply is the primary and the choke inductors. Since no oscillation is present, inductors act as a short and huge currents go through one of the Mosfets. This quickly burns the Mosfet then the other one opens and that one burns. In order to prevent such a thing from happening, several precautions are taken.

1. Current Limiter

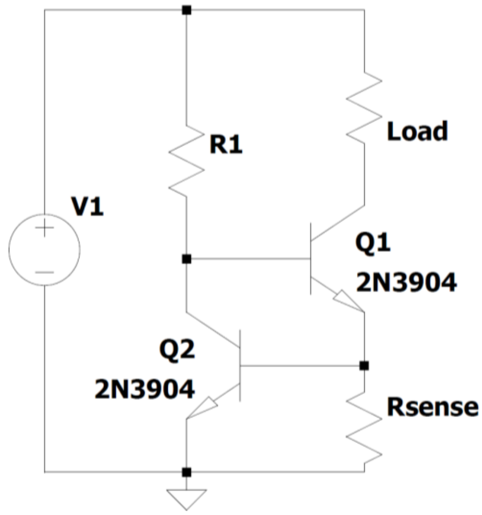

Figure 2. Current limiting circuit

The circuit in the figure above is the current limiter circuit that is used. Voltage over the Rsense resistor is used to determine the current and is feeded back to Q1 which changes the current over it is voltage over Rsense increases too much. The R1 resistor is there to adjust the maximum current. Rsense can't be used for that purpose since it is a source of inefficiency and should be chosen as small as possible. In this circuit, it's 0.1Ω.

As long as the current over the load less than the limit adjusted by R1, the transistor Q1 is in saturation, while Q2 is off. When the current rises above the limit, they both become forward-active. This can be shown in the figure below. As long as voltage over the sense resistor is below the threshold required to turn D1 on, $I_b = 0$ and $I_{load} = \frac{V_S - V_{CE}}{R_{load} + R_{sense}}$.

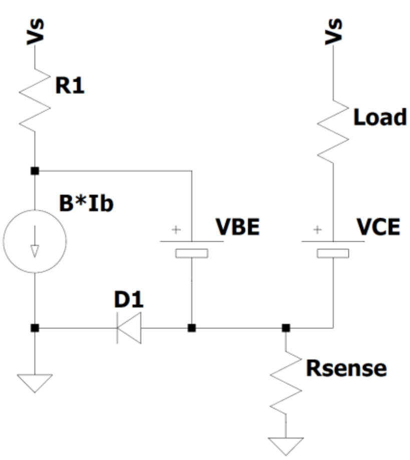

Figure 3. Q1 at SAT mode

When voltage over R_{sense} rises however, D1 turns on, $I_B \neq 0$ and the Q1 also becomes forward active. Voltage over R_{sense} is the same as V2 as can be seen below.

$$V_{sense} = V_2$$

$$I_{Rsense} = \frac{V_2}{R_{sense}}$$

$$I_{B1} = \frac{V_s - V_1}{R_1} - \beta I_{B2}$$

$$\beta I_{B1} - I_{Rsense} + I_{B1} = I_{B2}$$

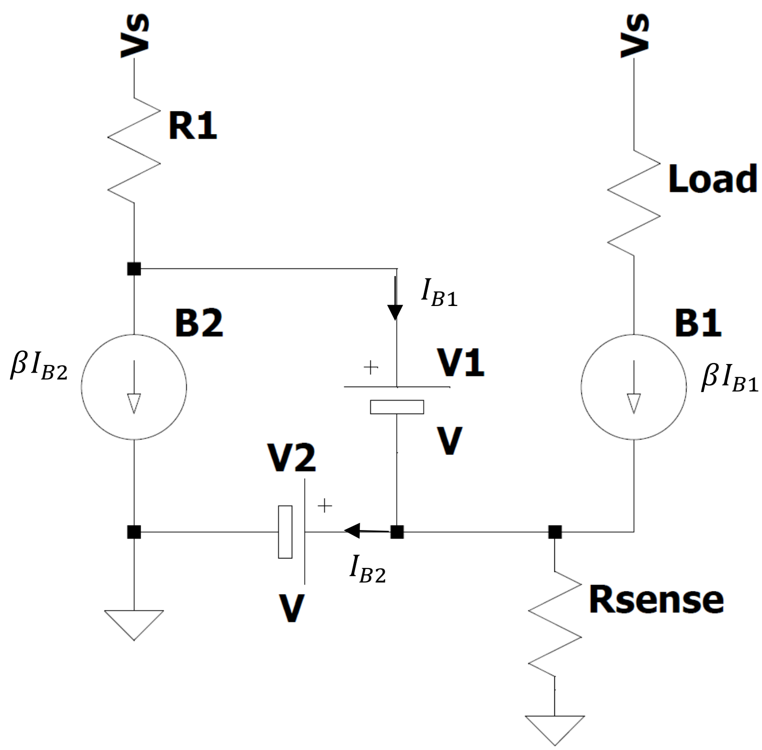

Figure 4. While current limiting, both in forward-active mode

$$I_{B1} = \frac{V_s - V_1}{R_1} - \beta\left((\beta + 1)I_{B1} - \frac{V_2}{R_{sense}}\right)$$

$$I_{B1} = \frac{\frac{V_s - V_1}{R_1} + \frac{V_2}{R_{sense}}}{\beta^2 + \beta + 1}$$

2. Capacitor

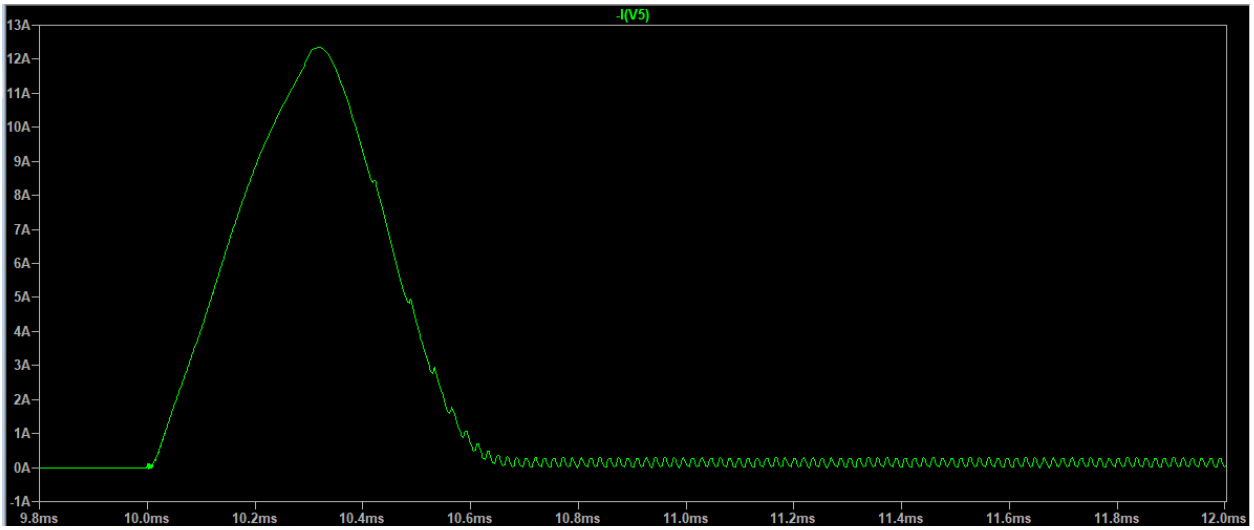

Figure 5. Inrush current of the circuit

The figure above gives the current needed to operate the circuit. At the steady state, it draws around 300mA peak but in order too kick start the circuit, 13A is needed. This isn't possible since we implemented a current limiter which limits the current around 600mA. To provide this short pulse of current, a large capacitor is introduced.

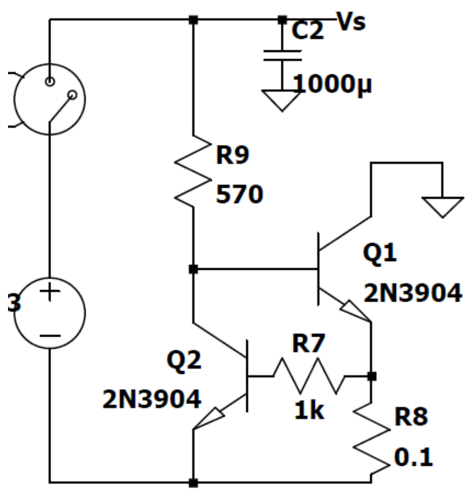

Figure 6. Capacitor with the current limiting circuit

First, a button is placed to turn on and off the ZVS circuit. A large capacitor is placed between voltage and the ground. When power supply is connected, first the capacitor charges. Then when the button is pressed, the step input is supplied from the capacitor so there is no problem of gradual input or not enough current.

3. Zener diodes and RC filter

Zener diodes are placed between gate source and drain source of the Mosfets. This makes sure that they don't exceed the specified absolute maximum voltages. This is important because the button causes some bouncing and the high frequency bouncing causes unwanted spikes. To decrease the bouncing, an RC circuit is placed in parallel to the button. This bouncing does not affect the circuit operation since it lasts for a short amount of time, however they have an affect the longevity of Mosfets.

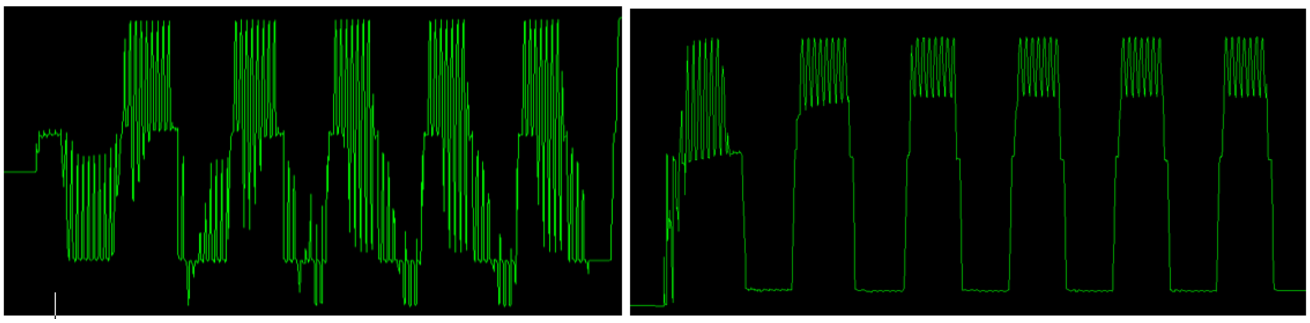

Figure 7. Difference between not using and using the RC filter

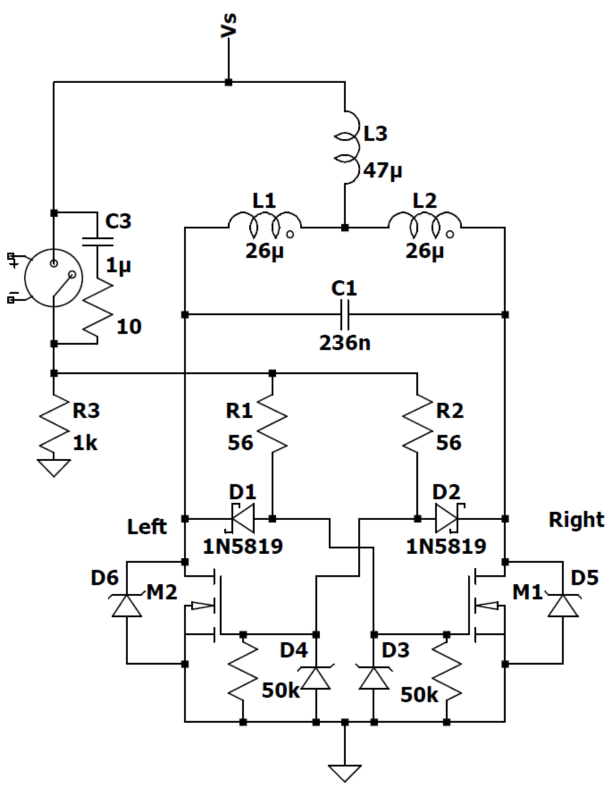

Figure 8. Finalized circuit schematic

Breadboard Prototype

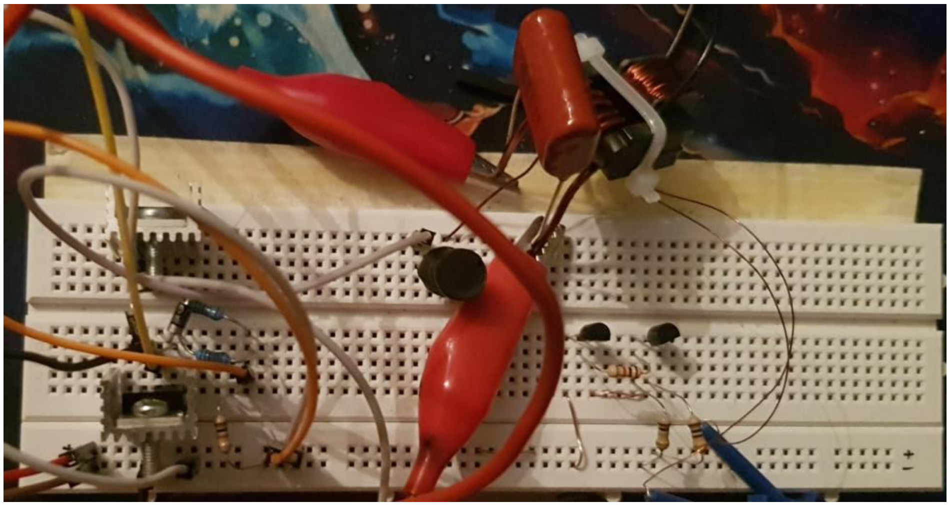

Figure 9. Breadboard implementation

On breadboard, circuit is tested. It's observed that the Mosfets don't get hot, but when current limiting is in effect, BJTs get very hot. They shouldn't be limiting current at normal operation, however they are probably the first element to fail in case of a problem. Also the Zener diodes which were 3.7V for Vgs and 7V for Vds were chosen very poorly since Vgs can go up to 7V and Vds can go up to 17V. New Zener diodes rated for 7.5V and 18V is order for the PCB.

Schematic and PCB

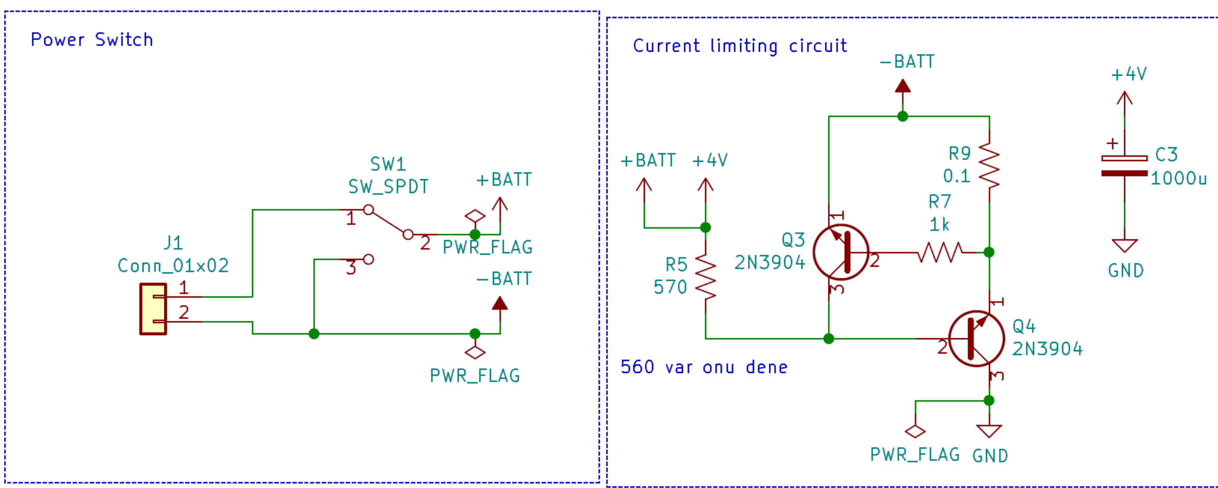

Figure 10. Power switch and current limiting circuit schematics

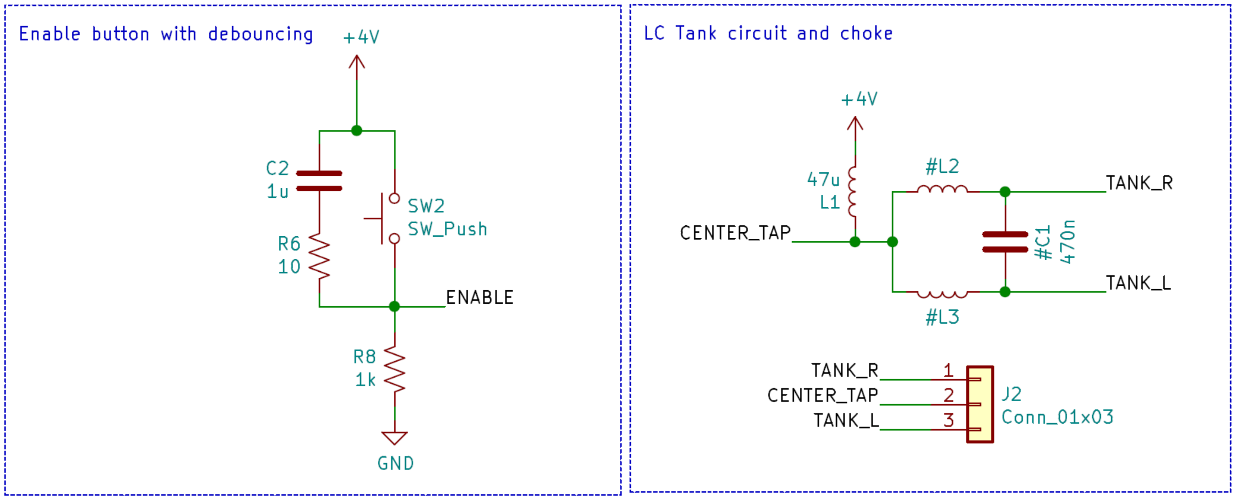

Figure 11. Pushbutton and transformer in the schematic

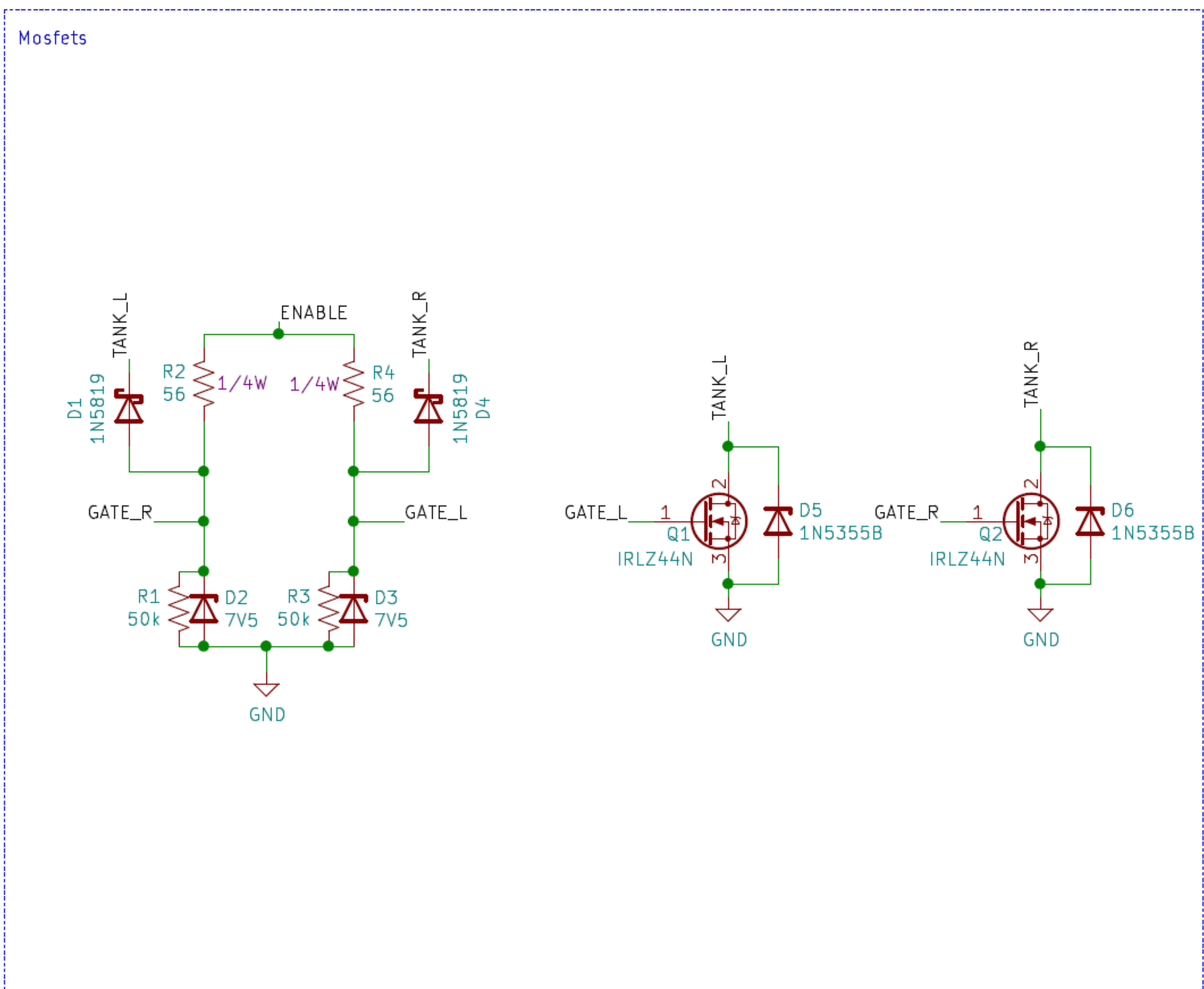

Figure 12. Mosfets in the schematic

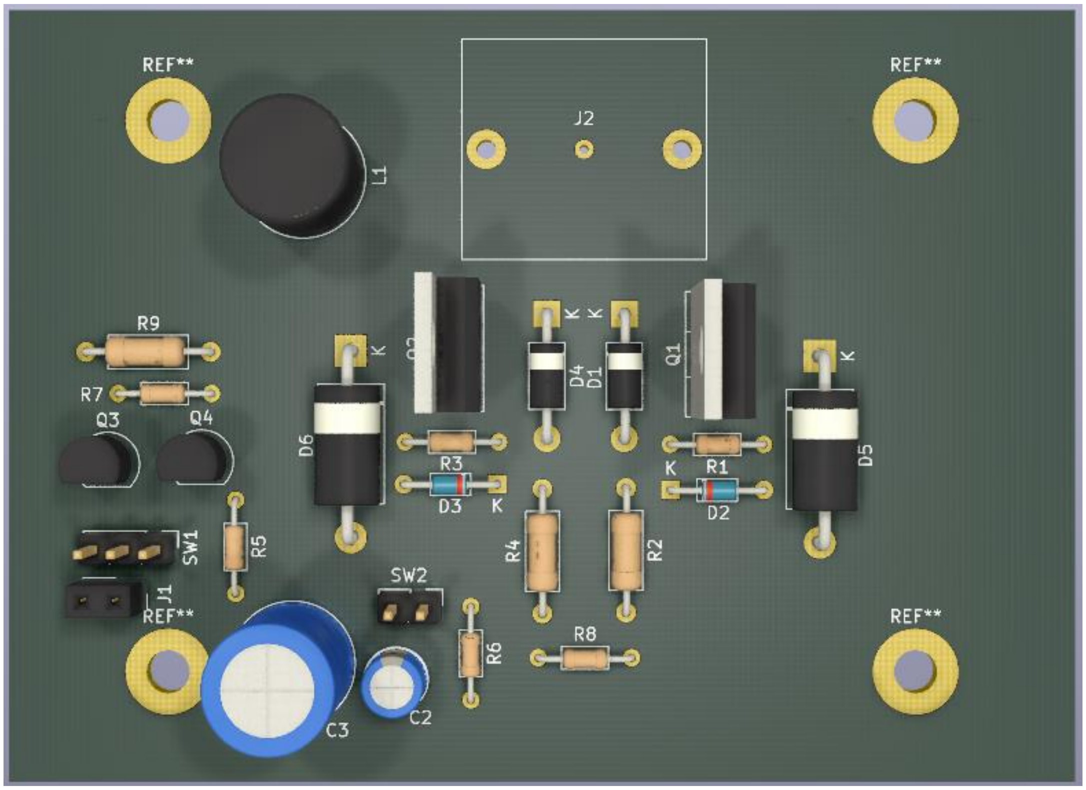

Figure 13. 3D render of the PCB design (Test points not included)

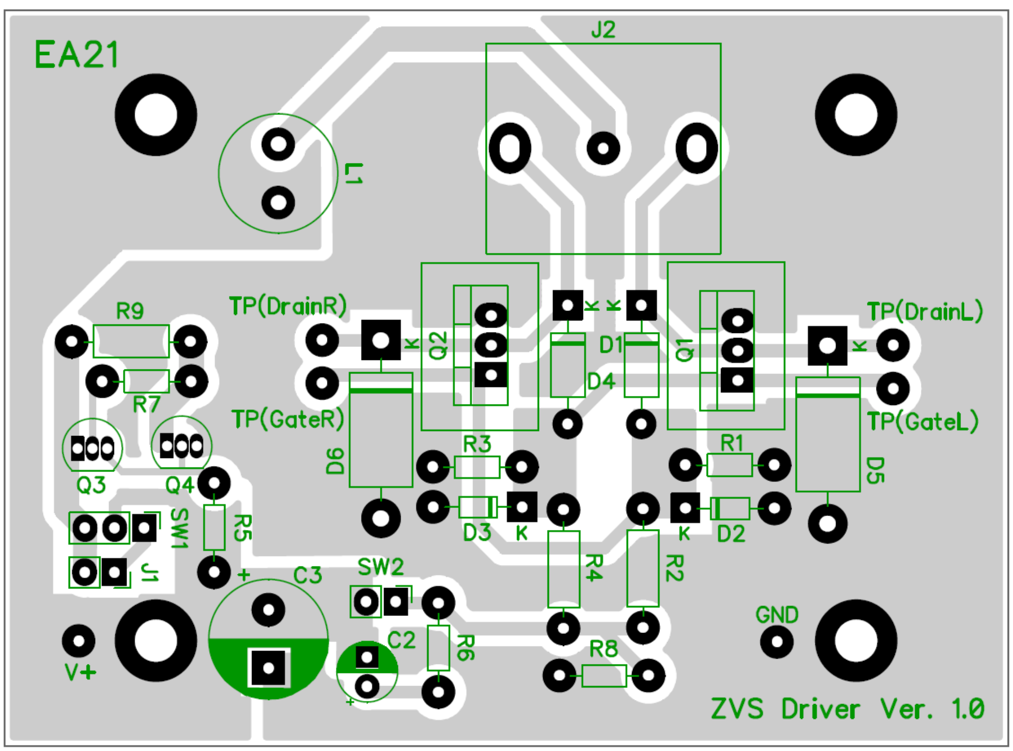

Figure 14. Finalized PCB design

Figure 15. Mounted PCB in the box

The box is drilled to include one power switch, one button two LEDs, the input wires and output terminal. They are all connected to male header on the PCB except for the red LED. Green LED is connected between power and ground and simply turns on when switch is on. The red LED is connected to the orange wires on the figure above. The orange wire is just one turn around the transformer so when there is an oscillation on the transformer, red LED turns on. In case circuit fails and Mosfets stuck, the red LED will be the indicator showing something is wrong. The output connectors are the same ones that are on a standard power supply.

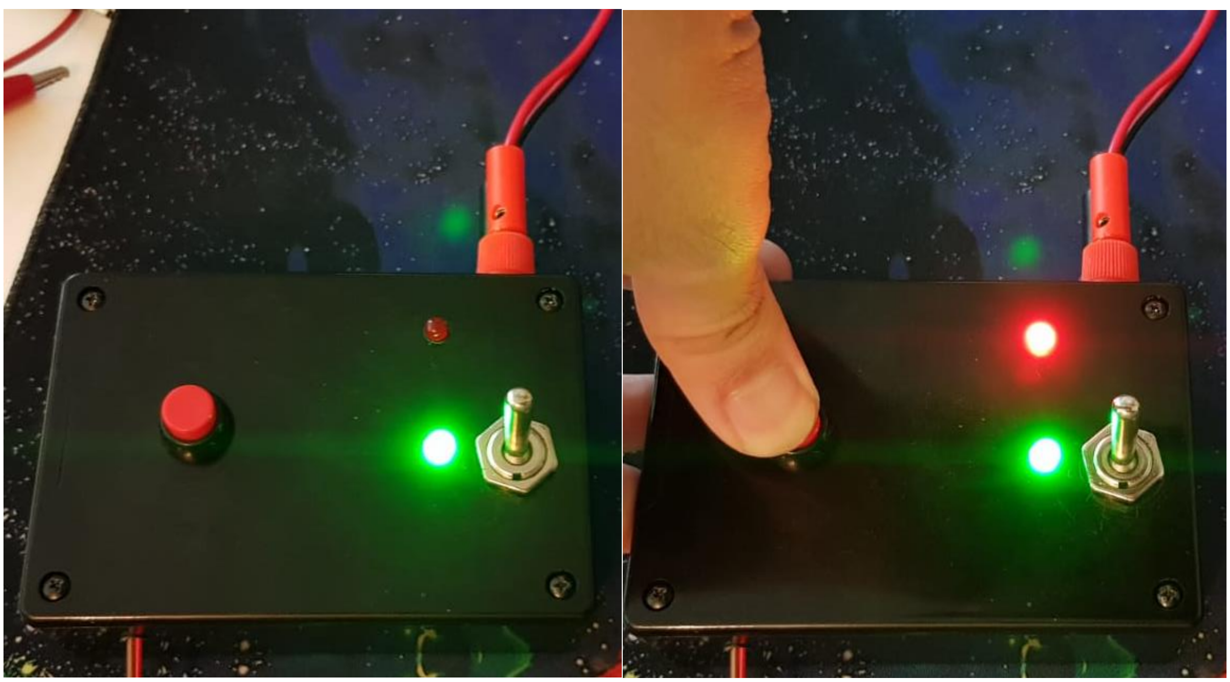

Figure 16. The external view of the device

Figure 17. 400V measurement after the AC output is rectified to DC

At 5.3V input, the output becomes 400V, but ignoring the voltage drop due to current limiter circuit, the gain is actually around 100. The drain source voltage of the Mosfets is 13V peak half sinewave and then the voltage over the inductor is 26Vpp.

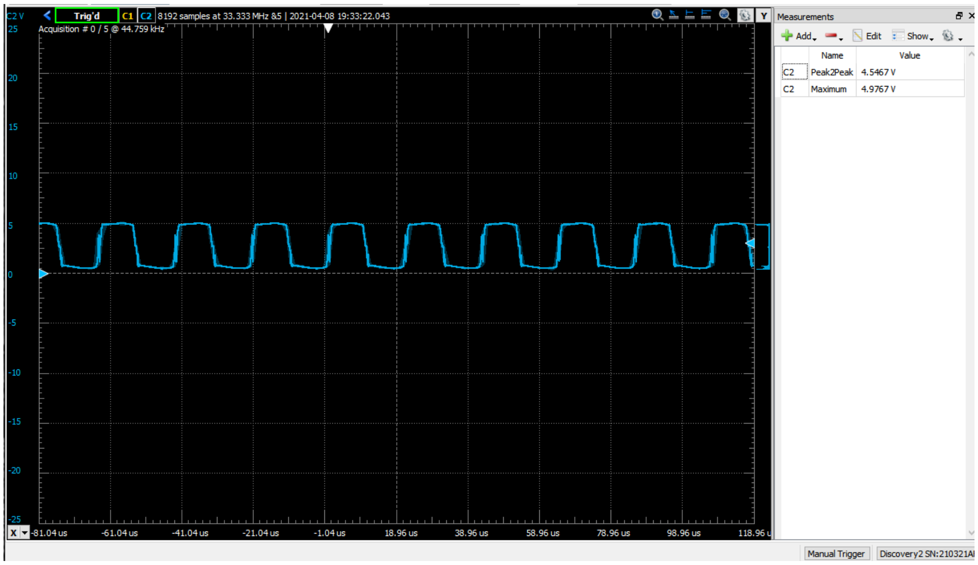

Figure 18. Gate source voltage of the left mosfet

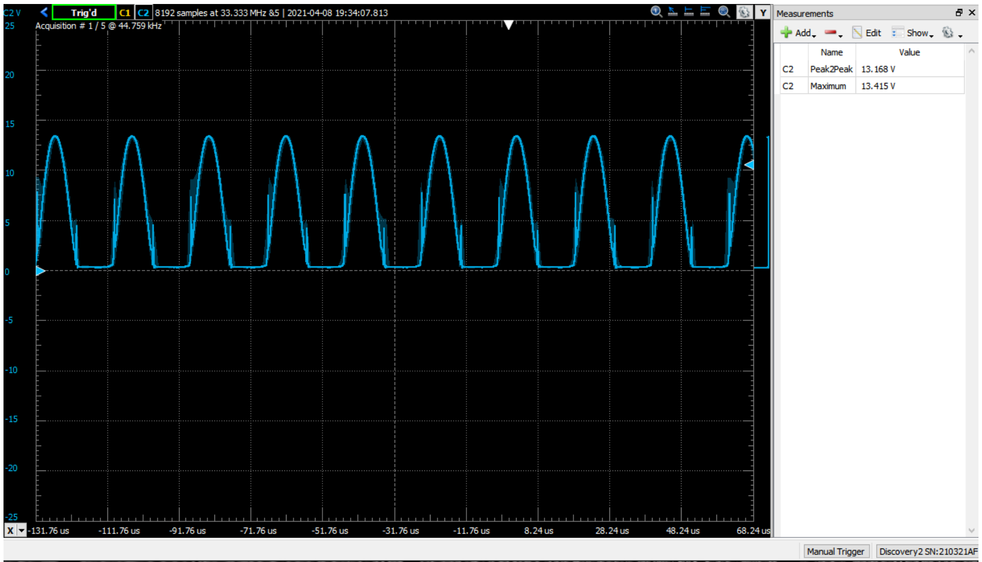

Figure 19. Drain-source voltage of the left mosfet

Notice that the gate source voltage is a saturated sine wave, while the drain source voltage is a half sine wave like explained previously. Also notice the spikes at the edges of the sine wave. Those spikes may cause problems if the AC voltage is directly used. In our cased we used the output only after rectifying to DC, but further improvements are necessary to get a pure sine wave in the output.

Bill of Materials

Component	Quantity	Unit Cost	Total Cost
1N5355B-HT 5W 18V ±5% Zener Diyot	2	1.26 TL	2.52 TL
4mm Born Jak (Orta Boy)	2	1.94 TL	3.88 TL
7V5 1/2W Zener Diyot	2	0.23 TL	0.46 TL
Resistor	9	0.04 TL	0.36 TL
HH062 Plastik Kutu Siyah (75x110x36mm)	1	12.77 TL	12.77 TL
470nF 630V Damla Tipi Polyester Kondansatör 20mm	1	1.52 TL	1.52 TL
IRLZ44N N Kanal Mosfet TO-220	2	6.28 TL	12.56 TL
TO220 Alüminyum Soğutucu - Beyaz	2	1.35 TL	2.7 TL

47uH 1.8A Kondansatör Tipi Bobin	1	2.25 TL	2.25 TL
1000uF 25V Kondansatör 5mm 10x16mm 2000Hrs	1	0.82 TL	0.82 TL
2N3904 Transistör Bjt Npn TO-92	2	0.18 TL	0.36 TL
1uF 63V Kondansatör 5x11mm	1	0.15 TL	0.15 TL
1N5819 1A 40V Schottky Diyot	4	0.23 TL	0.92 TL
DC158 Büyük Toggle Anahtar (On Off On) 6 Bacak 10A	1	8.07 TL	8.07 TL
IC191 Plastik Kısa Buton	1	3.09 TL	3.09 TL
5mm Led	2	0.20 TL	0.4 TL
High Voltage Transformer	1	20 TL	20 TL
Total	35		72.83 TL

Discussion

Although circuit indeed works, it is not perfect. The output voltage changes with the input voltage but it is not linear. The possible range of output voltage is also quite limited since below 2V as Vin, Mosfets simply stay off and after 7V, there is a risk of overheating. A better circuit would use an electronically variable input voltage, and separate voltage to drive the gates of the Mosfets. If a higher turn secondary could be used, the output range would be extended by a lot.

Another problem is that the output voltage drops when a load is connected since load “steals” energy from the LC tank. A future version should have a feedback mechanism to automatically adjust the input voltage to get a set output voltage. There is also the problem of the noise at the output, its voltage is not purely a sine wave and better Schottky diodes should definitely be used in a future version.

A different point of concern is the current limiter circuit. Although it works, it is quite inefficient and in case of a problem, the transistors would probably burn. This would protect the rest of the circuit but it is not ideal since the device breaks down after all. A better circuit would use a resettable circuit element in some way such that it still works after a fatal error. A microcontroller may be implemented for the feedback and controlling the output voltage, also dealing with the current limiting, error monitoring, etc.

Conclusion

In this project, a high voltage generator is designed, prototyped and then implemented on a PCB. The main components of the design consist of 2 BJT transistors and 2 Mosfets. The circuit uses the Mosfets to create a ZVS circuit that efficiently injects energy to a LC tank circuit. The inductor part is the primary of a high voltage transformer so the ZVS circuit effectively drives the transformer. In order to prevent the downsides of the ZVS circuit, various improvements are made to the basic design. Those improvements not only increase the longevity of the expensive and prone to break Mosfets but also provides a more stable high voltage generator. After building the PCB, the box is drilled for the LEDs and switches. The PCB is placed inside the box and the circuit operation is confirmed using the multimeter. As a result, the proposed device is designed and implemented successfully.