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Hybrid Desktop Power Supply

Arthur and Daniel Lim

----------ABSTRACT----------
Power supplies are one of the most essential equipment in labs and in daily life. The most basic type of power supply, the linear power supply, can be bulky, heavy and have low efficiency. In order to improve on all these drawbacks, a hybrid system that incorporates another type of power supply can be investigated. A switching power supply has high efficiency and low size, but has large amounts of ripple. The hybrid system would have the performance that is much better than a switching power supply, but have higher efficiency and smaller size compared to the linear power supply. To create this hybrid power supply, various schemes and layouts of a switching and linear power supply was researched. There are a limited number of journals that were related directly to this specific project. It was decided that a layout in series, where the switching power supply would down convert the largest, followed by a linear regulator to produce an output with less ripple. Then, the switching power supply block was first developed, followed by the linear regulator through design and simulation. The different modules that operate in the project are the microcontroller system, switching regulator and linear regulator. The microcontroller system allows the user to control the switching and linear regulator through voltage control and duty cycle changes. The switching regulator would reduce the voltage first, followed by the linear regulator. The linear regulator module would allow finer control of the output voltage, and is set by the microcontroller system.

KEYWORDS;- *IoT solution, HVAC, air-conditioning system, machine learning, climate change*

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I. INTRODUCTION

Power supplies are equipment necessary for laboratories, and therefore are required to deliver power with minimal ripple and maximums stability. To achieve this, linear regulators are used in power supplies. They are the simplest type of regulator, and achieve the desired output and ripple demanded in labs. However, they are often quite heavy, bulky, and have low efficiency. Another type of power supply, the switch-mode power supply, do not have these drawbacks of a linear power supply, being much smaller and much more efficient. The switching power supply would produce a large amount of ripple, which is not ideal in a laboratory as it will affect the device connected to said power supply. A hybrid solution containing both types of power supplies can be developed, which would have both the great efficiency of a switching power supply, reduced size and weight compared to a linear power supply, while improving the ripple from the output of a switching power supply.

II. OBJECTIVE

The motivation for doing this project is to improve the efficiency and size of laboratory power supplies, which in turn could reduce the amount of power wasted in laboratories. The goal is to try and improve on the current desktop power supplies size, weight and efficiency by combining the switching and linear power supplies. The objective of this project is to create a prototype that hybrid switching-linear power supply that targets an output of 30V DC up to 1A. In this proposed work, both switching regulator circuits and linear regulator circuits will be combined to create a hybrid system, along with a microcontroller system to control both types of power supply circuits and allow user control of the output voltage. The microcontroller system will control the switching regulator circuit using PWM control, and will use a voltage value to control the linear power supply circuit. A voltage sensor will be implemented to allow the microcontroller to detect the output voltage and change the PWM duty cycle value.

III. LITERATURE REVIEW

The linear power supply shares many components with the switching power supply, such as the rectifier, filter, with the difference being the regulator. The function of a linear power regulator is to decrease a higher voltage into a lower value. It achieves this by using a series transistor in the linear region of the voltage current curve to output the desired voltage. The transistor in this case acts as a variable resistor [1-6]. This also shows that the larger the difference between the input and output voltage, the larger the power lost and therefore the lower the efficiency of the linear regulator [7-17]. This heat also requires a large cooling solution to be attached to the

regulator, which increases the size and weight of the power supply. A switching power supply [18-24] uses inductors, capacitors, and a switching component to change the voltage. In an ideal scenario with ideal components, the switching elements have no resistance when they are in a "on" state and draw no current during the "off" state, which means it acts as an ideal off/on switch. This property of switch mode power supply is what gives its high efficiency compared to linear power supply, it does not dissipate the power into heat unlike the linear regulator [25-26]. The three basic topologies of the switch mode regulator are the buck, boost, and buck-boost regulators. To illustrate the basic operation of a switching power supply, only the operation of a buck converter is explained. When the switch is "on" or closed, the diode becomes reverse biased, and the input voltage causes the current to flow through the inductor [27-36], while charging up capacitor Cl. This current flow is represented as the blue line. The inductor will produce a back emf as current flows through it. When the switch is "off" or open, the inductor will cause a reverse voltage across the inductor, which causes the diode to be forward biased and allow current to flow through the load. The capacitor also discharges during this state. The LC filter will smooth out any ripple that was caused by the switch. Boost and buck-boost converters operate on a similar principle, but change around the positioning of the switch, inductor and capacitor. Buck is used to decrease voltage, boost is suited to increase voltage, while buck-boost uses a combination of both to be able to decrease or increase voltage in the same circuit. However, these topologies support a smaller input range, and to be able to change large voltages, isolated topologies need to be used. These include transformers to step up or step down the voltage. The topologies [37-45] that were investigated was the flyback converter. The flyback converter operates similarly to the buck converter, but where there is an inductor, a transformer instead is placed. A transformer allows different turns ratio for the input and output, which therefore allows a large difference for the input and output voltage. The transformer becomes a coupled inductor, and during the "on" cycle, the primary side inductor becomes charged as current flows through it. The diode disconnects the load from the transformer. When the switch turns "off", the secondary side diode becomes forward biased and current flows through, charging the capacitor and to the load [46-52]. The capacitor will then provide current to the load when the MOSFET switch is ON, and the secondary side transformer cannot provide current [53-60]. This topology is suited for a medium power range, typically 2-150W. For higher power [61-75], other configurations need to be used.

IV. Design

This section covers the design of the switching regulator circuit, linear regulator circuit, and microcontroller system of the project.

A flyback converter was used as the basis for the switching power supply block of this project, since it meets the power requirements of the output. First, the parameters of the project were used to start the calculations.

Vin=58V
Vout=30V
Pout=30W(30V×1A)
Freq= 250KHz
Duty cycle max=0.5

A frequency of 250KHz is selected, this is a common choice of frequency for flyback converters, and often what transformers are designed to work with. Larger frequencies also allow the use of smaller components. Using the output formula for a bridge rectifier, it was determined that the maximum voltage is 37.4V. A maximum duty cycle of 50% is chosen. From there, the inductance of the transformer primary side was calculated:

$$Lp = \frac{n \times Dmax^2 \times V_{IN\_Max}^2}{2 \times Fsw \times Kfr \times Pout} \qquad (1)$$

Where n is the estimated efficiency, Dmax is the maximum duty cycle, Vin_max is the maximum input voltage, Fsw is the switching frequency, Kfr is the ripple factor, and Pout is the power output by the regulator. N is set to 80%, as it is a common value for flyback converters. The ripple factor is chosen as 1

$$Lp = \frac{0.8 \times 0.5^2 \times 37.4^2}{2 \times 250 \times 10^3 \times 30} = 18.65\ uH \qquad (2)$$

From this equation, it can be found that the transformer primary side should have an inductance of 18.65uH or more. Next, the turns ratio was found in this equation

$$n_{s1} = \frac{V_{in\_max} \times D_{MAX}}{(1 - D_{MAX}) \times (V_O + V_D)} \qquad (3)$$

Where V_O is the output voltage and V_D is the diode forward voltage drop.

$$n_{s1} = \frac{37.4 \times 0.5}{0.5 \times 30.7} = 1.218 \quad (4)$$

1.218 is the turns ratio that was derived from this equation, but this value might not be suitable in practical circuits, so a 1:1 ratio will be used in the simulations. Next, the specifications of the MOSFET are determined, specifically the maximum voltage.

$$V_{DS\_MAX} = V_{in\_MAX} + \frac{D_{MAX} \times V_{in\_min}}{1 - D_{MAX}} \quad (5)$$

Where V_{in_min} is the minimum input voltage.

$$V_{DS\_MAX} = 37.4 + \frac{0.5 \times 37.4}{1 - 0.5} = 74.8V \quad (6)$$

This shows for selecting MOSFET component, it should be able to withstand 74.8V. The next equation calculates the maximum current.

$$I_{pk-pk} = \frac{Pin}{D_{MAX} * V_{in\_min}} + \frac{D_{MAX} * V_{IN\_MIN}}{2 * F_{sw} * L_{p\_max}} \quad (7)$$

Where P_{in} is the power input the regulator, which is the product of the voltage and the current input. L_{p_max} is the inductance of the primary side transformer derived earlier.

$$I_{pk-pk} = \frac{30 \times \frac{1}{0.8}}{0.5 \times 37.4} + \frac{0.5 \times 37.4}{2 \times 250000 \times 0.000186} = 2.2A \quad (8)$$

The MOSFET chosen must be able to support 2.2A. The next step is to calculate the voltage that the rectifier diode has to support.

$$V_{D\_PK} = V_{out} + \frac{V_{in\_max}}{n} = 30 + \frac{37.4}{1.28} = 59.2 + 40\%(safety\ margin) = 82.9V \quad (9)$$

To calculate the voltage ripple at the output, an output capacitor needs to be chosen first.

$$\Delta V_o = \frac{D \times I_o}{F_{sw} \times C} \quad (10)$$

Where ΔV_o is output voltage ripple, Io is the output current, D is the duty cycle, Fsw is the switching frequency and C is the capacitance of the capacitor. If a 250uF capacitor was used, the output voltage ripple can be calculated.

$$\Delta V_o = \frac{0.5 \times 1}{250kHz \times 250uF} = 8mV \quad (11)$$

From this calculation, it was determined that there should be a 60mV output ripple when running at 50% duty cycle.

To improve this design, a snubber circuit was added to the primary side of the transformer. This is needed to improve the voltage spikes that occur due to ringing. First, the maximum capacitor voltage was determined.

$$V_{C(MAX)} = V_{DS\_MAX} \times 0.1 + \frac{D_{MAX}}{1 - D_{MAX}} \times V_{IN(MIN)} \quad (12)$$

Where $V_{IN(MIN)}$ is the minimum input current and V_{DS_MAX} is the maximum MOSFET voltage.

$$V_{C(MAX)} = (74.8 \times 0.1) + \left(\frac{0.5}{1 - 0.5} \times 37.4\right) = 44.8V \quad (13)$$

The next part is to calculate the power in the snubber circuit, using the equation below

$$P_{R\ SNUBBER} = \frac{I_{P(PEAK)}^2 \times L_{leak} \times F_{sw}}{2} \quad (14)$$

Where L_{leak} is the leakage inductance, which is 2% of the primary inductance, and Ipeak is the peak current of the mosfet.

$$P_{R\ SNUBBER} = \frac{2.2^2 \times 0.373uH \times 250kHz}{2} = 0.23W \quad (15)$$

The next part is to determine the resistor value for the snubber, using the power in the snubber and the capacitor voltage values.

$$R_{SNUBBER} = \frac{(V_{C(MAX)})^2}{P_{R\ SNUBBER}} = \frac{44.8^2}{0.23} = 8.7k\Omega \quad (16)$$

The next part is to determine the capacitor value of the snubber circuit using the resistor value

$$C_{snubber} = \frac{1}{\Delta V_c \times R_{SNUBBER} \times F_{sw}} \quad (17)$$

Where ΔV_c is the snubber capacitor ripple, which is set to 10%.

$$C_{snubber} = \frac{1}{10\% \times 8.7k \times 250k} = 4.60nF \quad (18)$$

The output voltage formula for a flyback converter is shown below:

$$V_{out} = \frac{N_s}{N_p} \times \frac{D}{1-D} \times V_{in} \quad (19)$$

Where Vout is the output voltage, Vin is the input voltage, Ns is the secondary side turns, Np is the primary side turns, and D is the duty cycle selected. If a 1:1 turns ratio is selected, and a 37.4Vpeak the following voltage values that would be output are shown in the table below.

Table 1: Calculated voltage output results

Duty cycle	Voltage
5%	1.96V
10%	4.15V
15%	6.6V
20%	9.35V
25%	12.4V
30%	16.0V
35%	20.14V
40%	24.9V
45%	30.6V
50%	37.4V

This calculation is done assuming the input to the flyback converter was from a DC source, which is not the case with this project. Since the prototype uses an AC input rectified into DC, capacitors will need to be placed after the bridge rectifier to create DC. The value of the capacitors is determined by using simulation, as shown below.

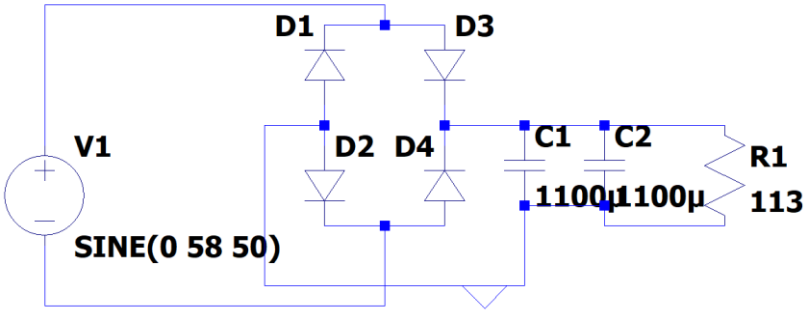

Figure 1: Simulation used for capacitor value

The AC signal used is 58Vpeak, which is equivalent to 41.5 Vrms. The steps to obtain the load resistance is used below:

$$P_{out} = P_{in} = 30W \quad (20)$$

$$I_{in} = \frac{Pin}{Vin} = \frac{30}{58} = 0.517A \quad (21)$$

$$R_{load} = \frac{Vin}{Iin} = \frac{58}{0.517} = 113A \quad (22)$$

The result of this simulation is shown below:

The result shows that using 2 capacitors at 1100uF, the voltage ripple is at 1.6V, which is small enough for the flyback circuit to operate properly. To improve from this ripple, much more capacitors and higher values need to be used, which is not practical for the actual circuit, and hence 2 1100uF capacitors are chosen.

The ESR or equivalent series resistance of capacitors are another factor that needs to be calculated during the design phase of this project. To calculate this, the formula below is used.

$$ESR = \frac{\tan(\delta)}{2\pi fC} \quad (23)$$

Where $\tan(\delta)$ is the tangent of the loss angle, which is given in the data sheet for most capacitors, f is the frequency given in the datasheet, and C is the capacitance of the capacitor. Using a datasheet of a 100V 1000uF capacitor, where the $\tan(\delta)$ is given as 0.08, the frequency is 120Hz, the ESR can be determined.

$$ESR = \frac{0.08}{2*\pi*120*0.001000} = 0.106\Omega \quad (24)$$

So, when 2 1000uF capacitors are used, the total ESR would be 0.212 ohms. Which is low and therefore suitable to use in this project. For the capacitor on the secondary side, a 63V 220 uF capacitor was used, and below is the calculation if its ESR.

$$ESR = \frac{0.10}{2*\pi*120*0.000220} = 0.603\Omega \quad (25)$$

The calculated ESR is 0.603 ohms, which is still low and therefore will not affect the circuit output power.

Using all the calculated values, the circuit diagram can be made, as shown below:

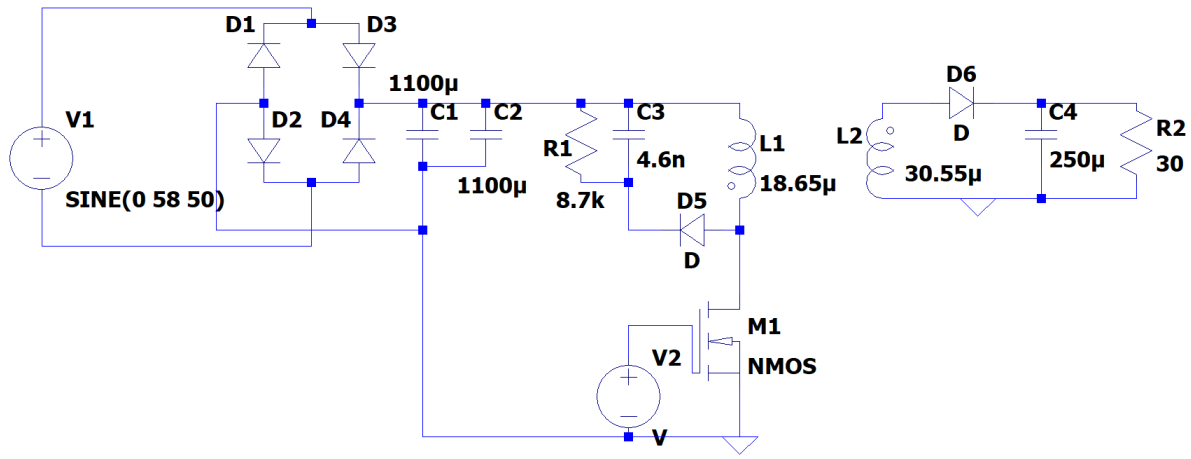

Figure 2: Flyback converter derived from calculations

This circuit uses all the values derived from the calculations, except for the diode and MOSFET. The secondary side inductance of the transformer is calculated using the formula below.

$$\frac{L1}{L2} = \left(\frac{N1}{N2}\right)^2 \tag{26}$$

The linear power supply is mainly comprised of a BJT transistor that has with feedback through an op amp. The BJT will be the component that reduces the voltage to the final output level, controlled by the voltage in the base of the transistor. The microcontroller will become the voltage reference that the op amp connects to, and therefore can change the voltage at the base. Below is the diagram of the linear power supply.

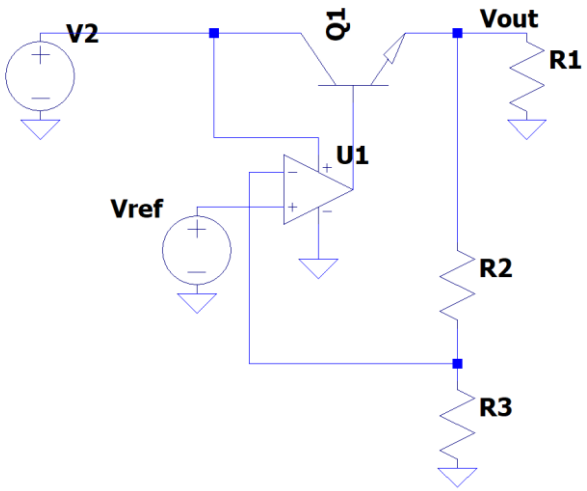

Figure 3: Diagram of linear regulator

R1 is the load, R2 and R3 are used to adjust the gain of the Vref to Vout. The formula of Vout in reference to Vref is shown below:

$$V_{out} = V_{ref} * (1 + \frac{R2}{R3}) \tag{27}$$

In the project, Vref will be connected to the microcontroller, and therefore R2 and R3 will be determined by the range of voltage that the microcontroller can output.

Once the microcontroller has been chosen, the next step is to design the system around the microcontroller in order for the project to operate. Below is the pinout diagram of the PIC18F4550 with the connections needed for this project.

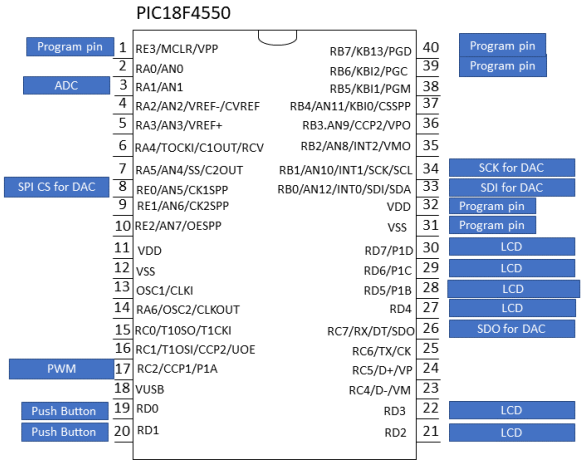

Figure 4: Pinout of PIC18F4550

Pin AN1 will be used for the ADC, as this pin is connected to the microcontroller's internal analog to digital converter. This will be used as a voltage sensor to measure the output voltage. The external DAC communicates via the SPI protocol, and hence the appropriate pins that contain the SPI functionality must be used, such as SCK, SDI, and CS pins. The PWM signal will be generated from the RC2 pin, as that pin is connected to the microcontroller's PWM generator. The LCD is operating in 4-bit mode to reduce the number of pins taken up by the LCD, and is connected to RD2-RD7 pins. Below is the full circuit diagram for the microcontroller in this project, which contains more details about how each external components are connected.

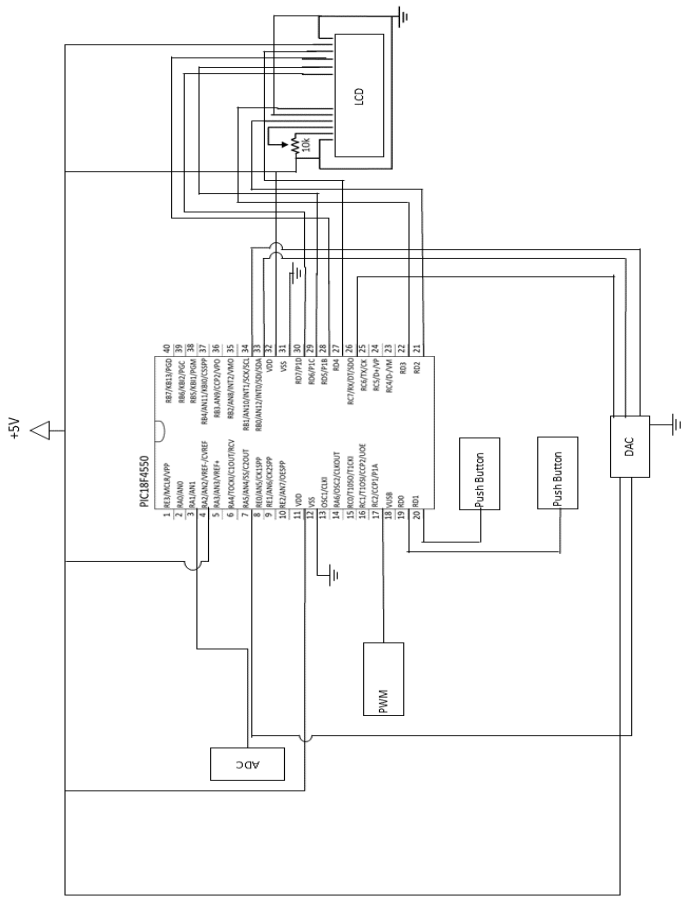

Figure 5: Full circuit diagram for Microcontroller

V. FIRMWARE DESIGN

Software and algorithms are developed for the PIC18F4550, in order to control the entire power supply prototype. The software will be shown in flowcharts in order to describe the function of the software. Below is the main flowchart of the software.

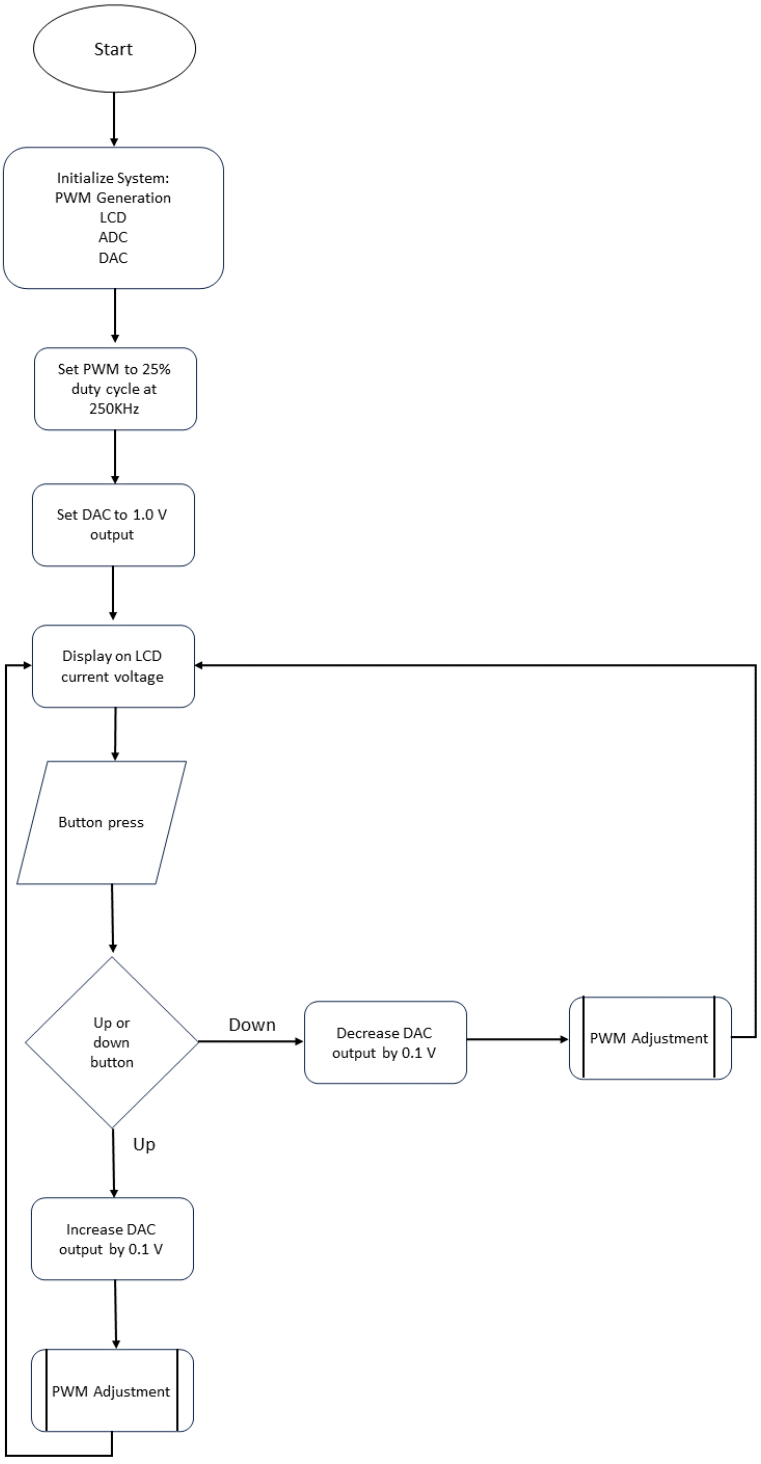

Figure 6: Main Flow Chart

First once the system is powered on, the microprocessor first initializes all the necessary functions needed for this prototype, including the PWM generation, LCD output, ADC inputs, and DAC via the SPI protocol. The next step is to enable the PWM signal generation set to 250KHz and set at 25% duty cycle. This is because the system is set to output at 10V at start up, and 25% duty cycle is a suitable value for the switching power supply.

Then, the DAC is enabled and set to output at 1V. With the op-amp feedback setup shown in linear regulator design section, the final output of the linear power supply circuit will be 10x the output of the DAC, and hence a 1V output will result in a 10V output from the linear regulator circuit. The next step is to send the current voltage value to the LCD for the user to be able to see.

Once the LCD is displaying the value, the system will continue to output until the user changes the voltage output by pressing one of the two buttons. If the up button is pressed, the system will then adjust the DAC output by changing the output value by 0.1 V, which will increase the voltage by 1V. Then, a PWM component will adjust the switching duty cycle if it enters a higher value. Then the system will update the increased value in the LCD. A similar flow will be initiated if the user pressed the down button, which decreases the voltage by 0.1V from the DAC output, which will decrease the voltage by 1V in the final output. Then the LCD will be updated with the final value. The PWM will be adjusted in a similar manner to the results from the switching power supply section.

VI. SIMULATION

The simulation used in this section is based on the actual components from the component selection, and as shown in the component selection, there are compromises made from the limited parts available. For example, the ideal transformer would be custom made by the manufacturer to the exact specifications derived from the calculations, but due to cost and feasibility of making a custom transformer, one was selected which was could output the desired voltage and current.

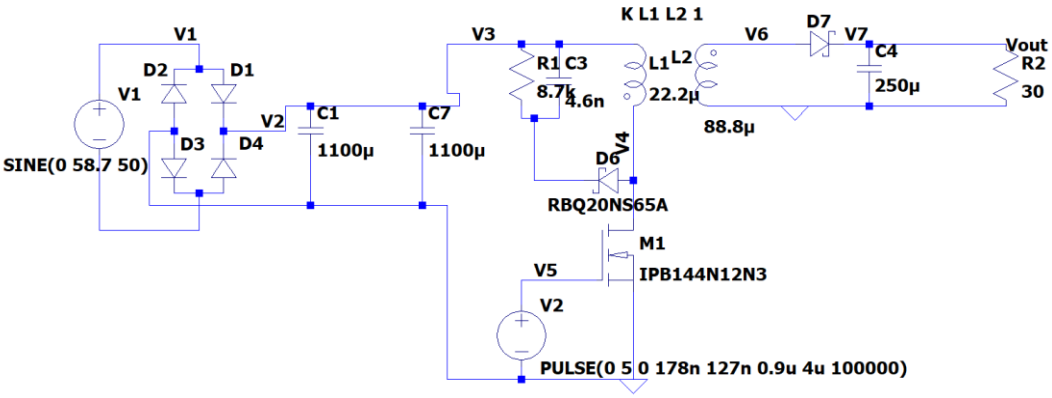

Figure 7: Simulation of Flyback converter

Since the actual components do not have LTspice models, other ones with similar specifications were chosen instead. This would give a close approximation to the real circuit. There are various points placed in the circuit such as V1, V2, etc. These will be points used to illustrate the location of the following plots.

This is the plot of V1 and V2

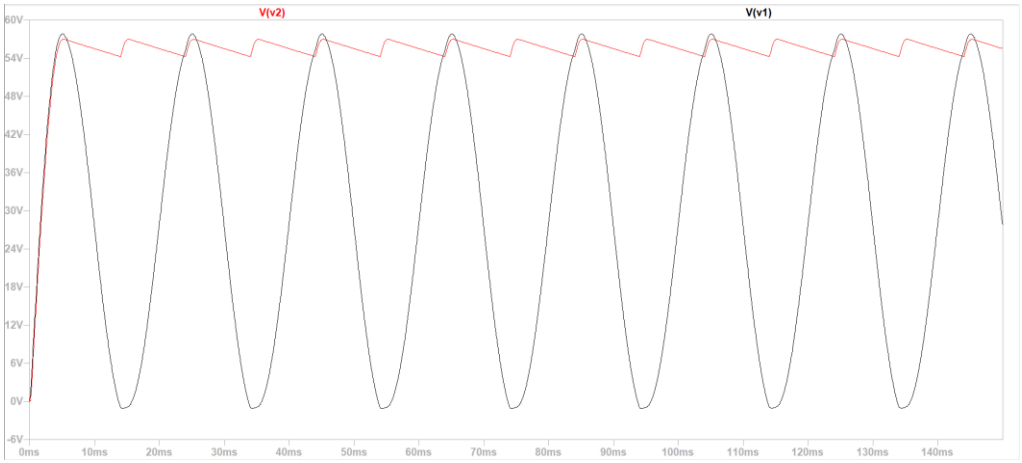

Figure 8: Plot at V1 and V2

the figure shows, V1 is the 58Vpeak AC input, while V2 is the input after rectification and smoothing from the capacitor. This plot shows that the bridge rectifier and capacitors are functioning correctly, smoothing out an AC signal into a much flatter DC one, though it still has ripple due to the limitations of the capacitors. The plot at V3 is the same as V2 as it is at the same point. The plot of V4 is shown below.

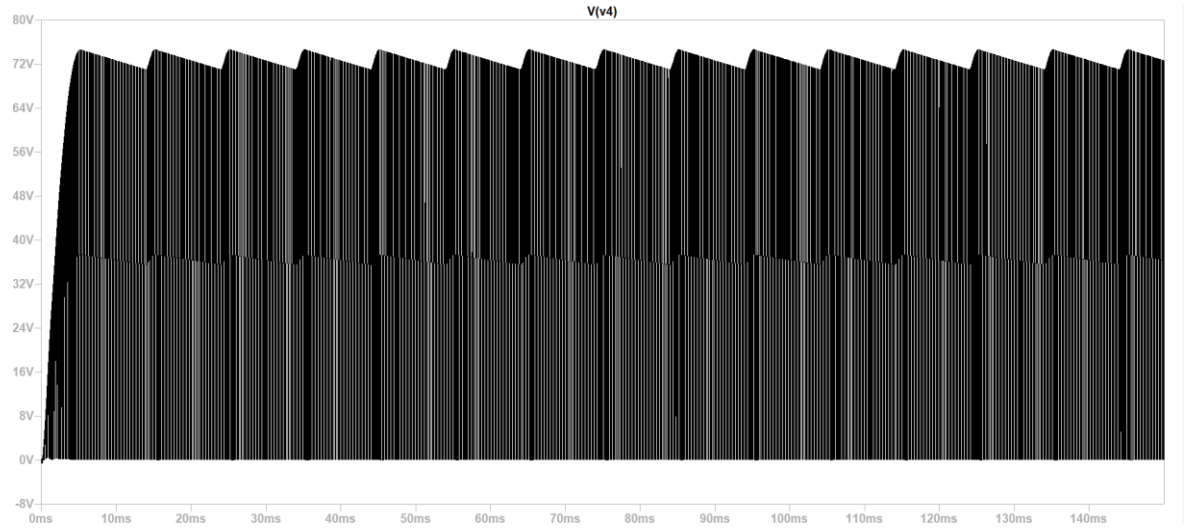

Figure 9: Plot at V4

This plot shows the switching action caused by the MOSFET which goes through the primary side of the transformer. A zoomed in plot is shown in the figure below

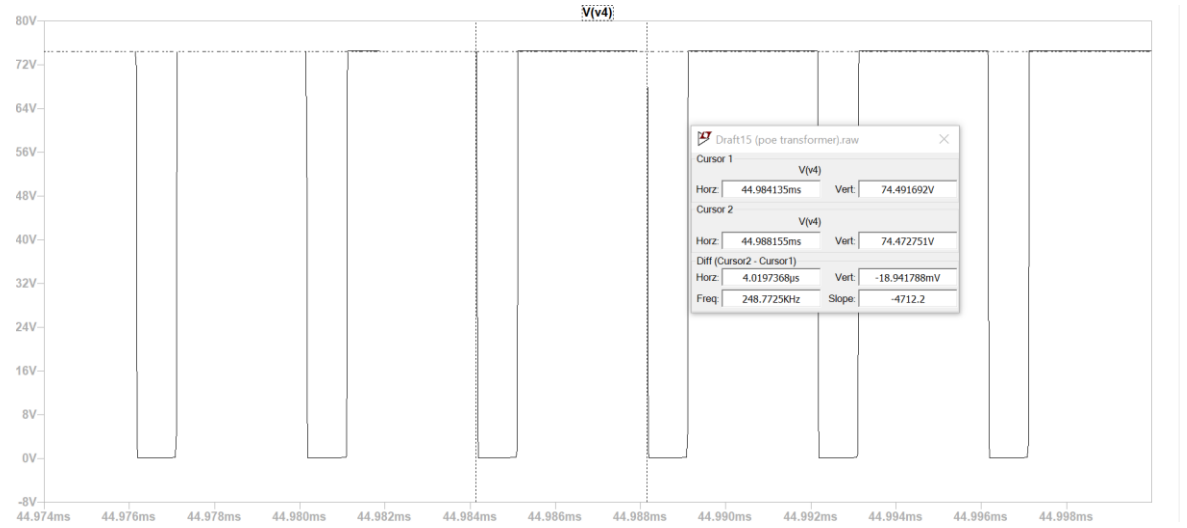

Figure 10: Zoomed in plot of V4

Once the plot is zoomed in, it can be analysed for its frequency along with its peak and lowest value. Here it can be seen that the frequency is 250kHz, matching the desired frequency from the MOSFET, and it is correctly switching off to 0V. The plot below illustrates the PWM signal used to control the MOSFET at V5.

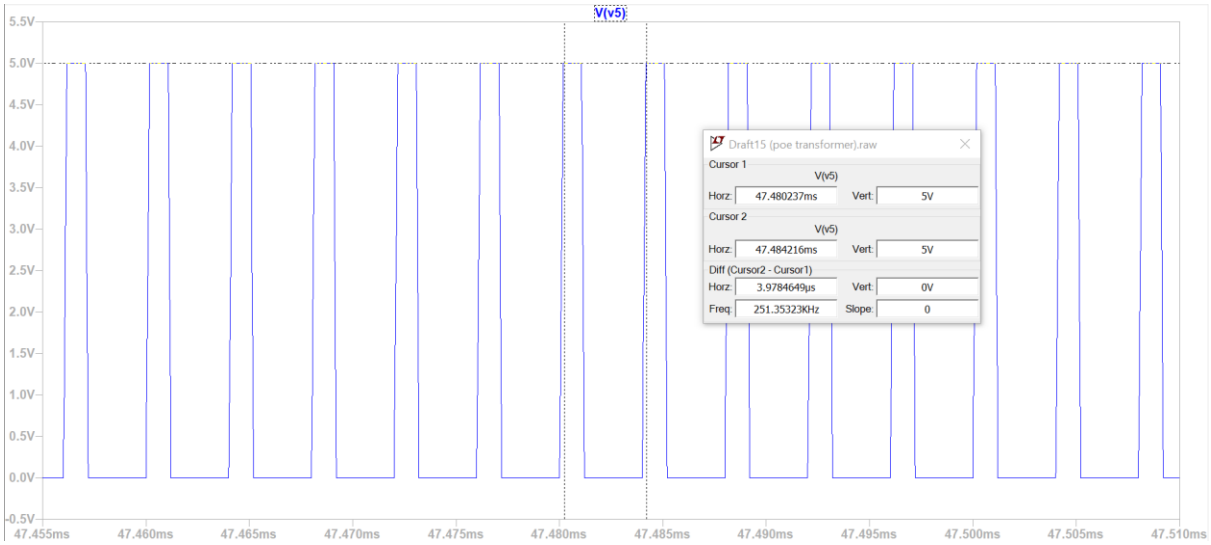

Figure 11: Plot at V5

This plot shows the PWM signal generated by the microcontroller, passed through the gate driver to increase the current, and into the gate of the MOSFET. This signal controls how the MOSFET opens and closes, and therefore the switching action. The plot below shows the signal at the secondary side of the transformer at V6.

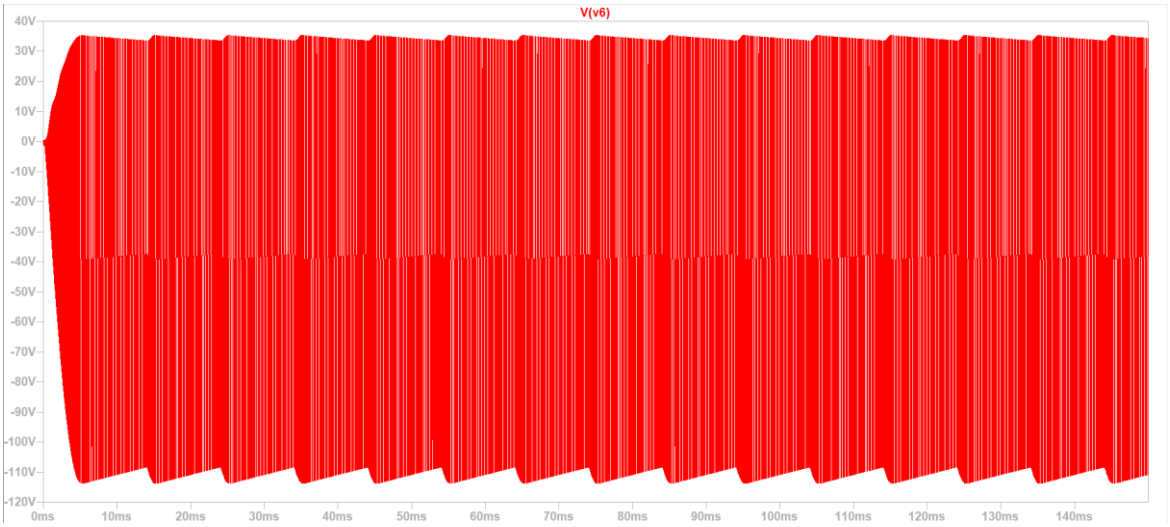

Figure 12: Plot of secondary side at V6

This plot shows that the negative voltage might be larger than expected, most likely due to the much larger secondary inductance. This issue means that the secondary side diode will need to be changed to one that can handle much larger value, like 150V or 200V. A zoomed in plot of the secondary side is shown below.

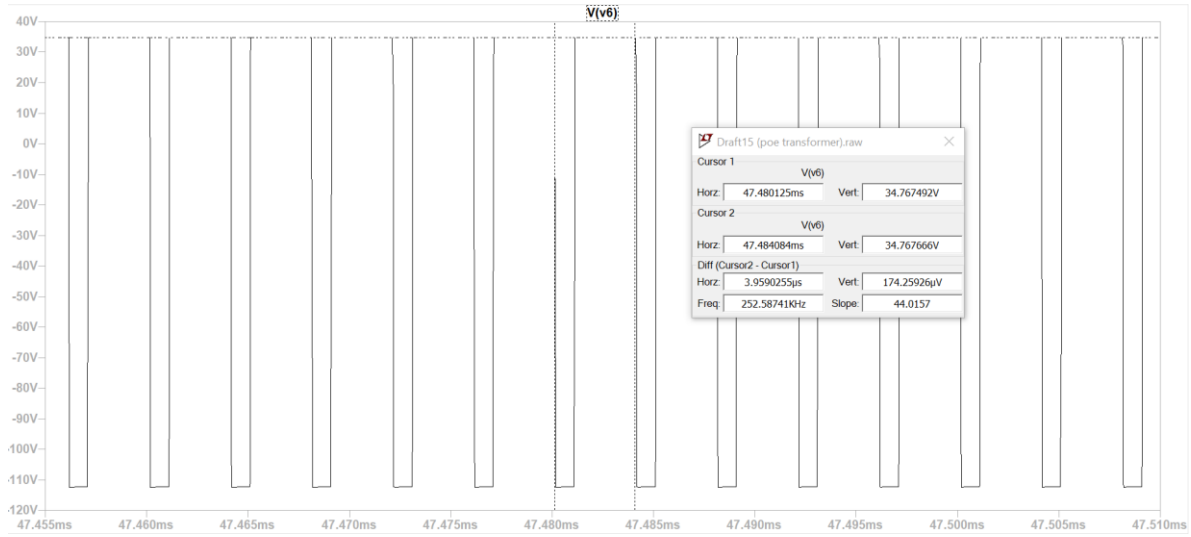

Figure 13: Zoomed in plot of the secondary side

This figure illustrates that the frequency is correct at 250kHz, and shows a clearer picture of the waveform at the secondary side. The positive value is at 35V, and the negative value is at -110V. The figure below shows the secondary side after it has been rectified by the diode at point V7 and Vout.

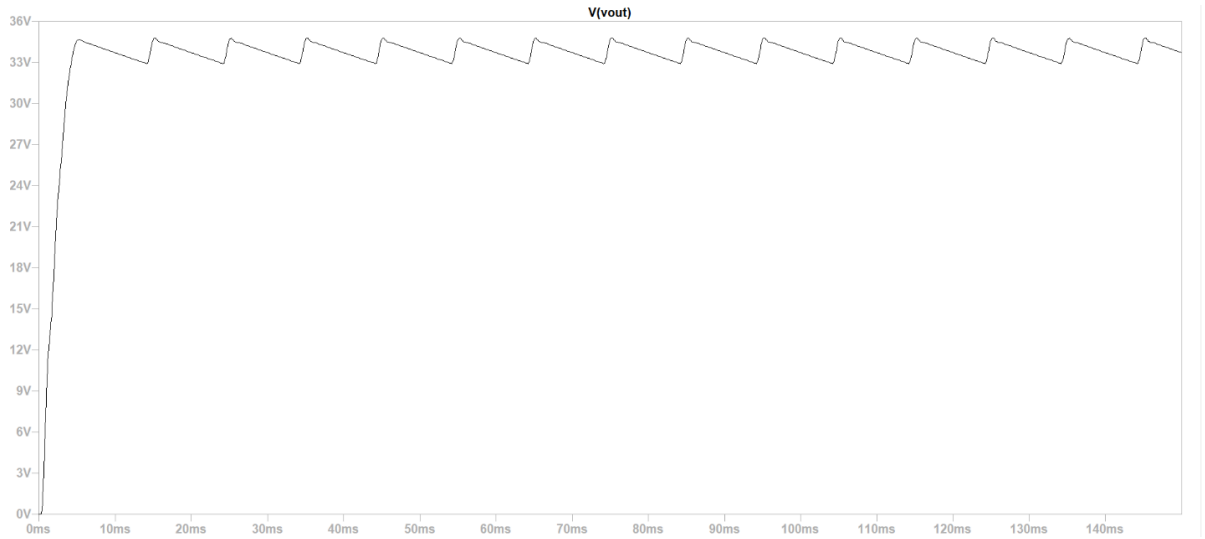

Figure 14: Plot of V7

This waveform shows the ripple that a switching power supply generates, and why the linear power supply would be incorporated to smooth out the signal further. Below is a zoomed in plot to show how much ripple is being produced.

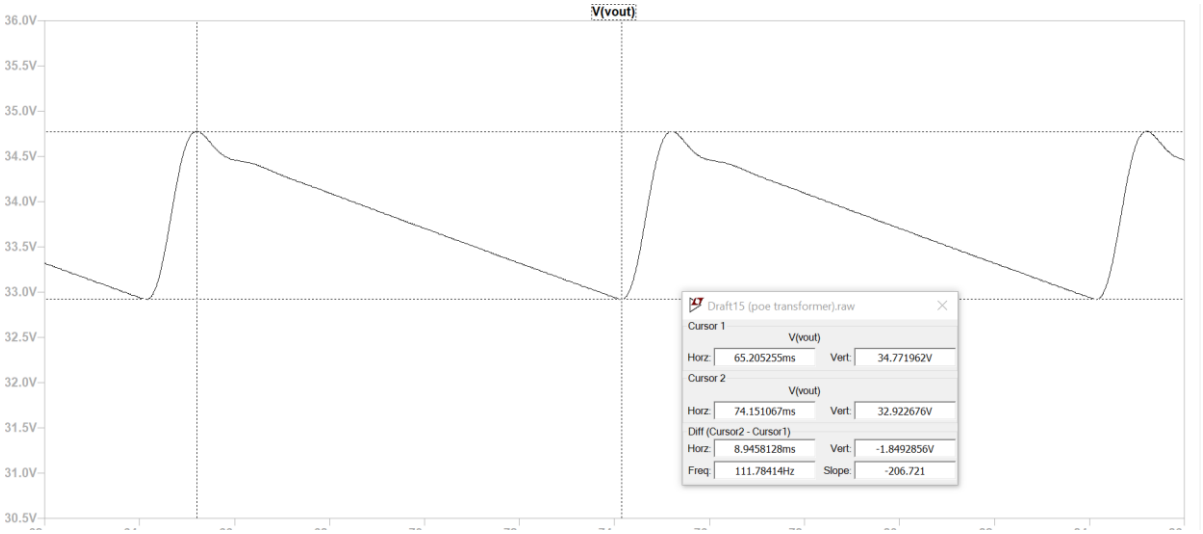

Figure 15: Zoomed in plot of V7

This plot shows the ripple is 1.8V, which not a small amount of ripple, and would be unacceptable for a laboratory use case, and hence the need for the linear regulator.

Below is the table of the duty cycle against the voltage output of the switching power supply.

Table 1: Duty cycle vs voltage output of simulation

Duty Cycle	Voltage
2.5%	5.3V
5%	7.8V
7.5%	10.85V
10%	14.1-14.07V
12.5%	17.7-17.5V
15%	21.6-21.1V
17.5%	25.7-24.9V
20%	30.1-28.9V
22.5%	34.75-32.9V

This shows that the minimum output of the switching power supply simulation is 5.3V, which means the linear regulator will be the circuit that reduces the voltage for reducing the voltage to below 5V.

Below is the simulation of the linear regulator circuit, using same design decided in the design section.

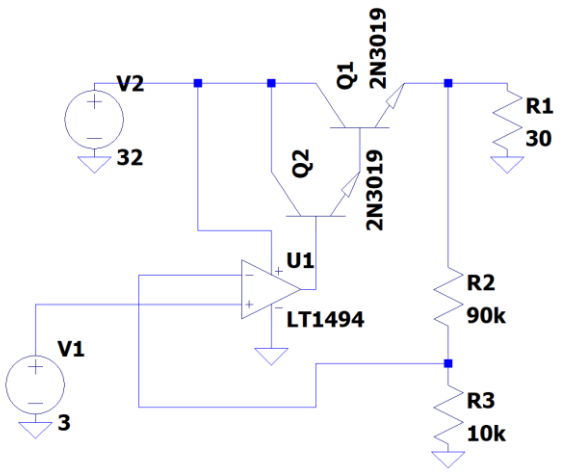

Figure 16: Simulation of series pass voltage regulator

The transistors were chosen since they have similar combined gain to the Darlington pair chosen in component selection. Using the formula below, the values of R2 and R1 were chosen to create a gain of 10 for Vref to Vout.

$$V_{out} = V_{ref} * \left(1 + \frac{R2}{R3}\right) = V_{ref} * \left(1 + \frac{90k}{10k}\right) = V_{ref} * 10 \qquad (28)$$

The plot below shows the output of this regulator.

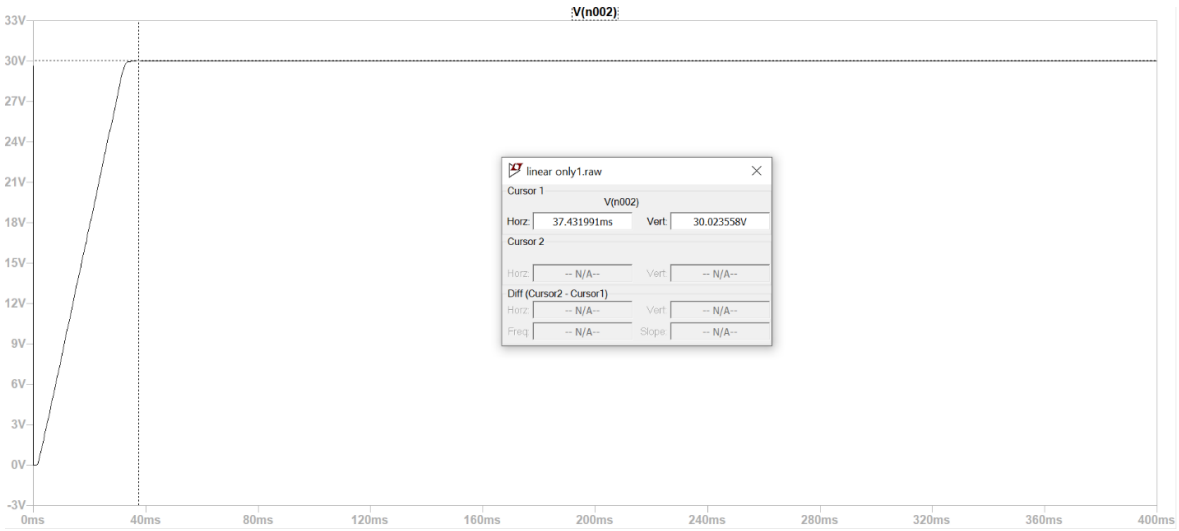

Figure 17: Plot of linear regulator output

This shows the linear regulator circuit is operating as intended, as the Vreference is set to 3V, and the output of the circuit is 30V. The waveform below shows the output when the Vreference is set to a different value, 2.1V.

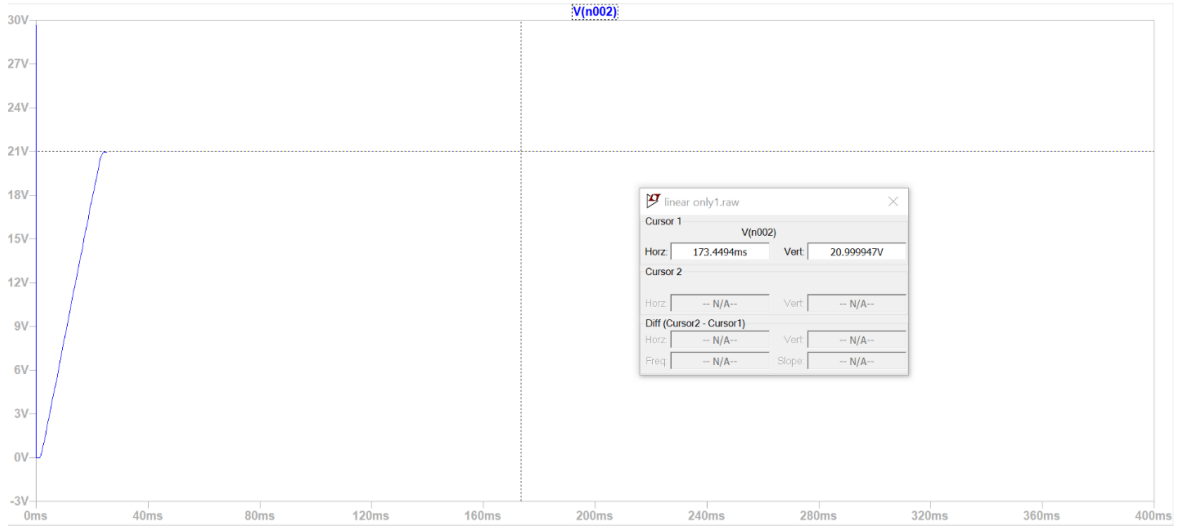

Figure 18: Plot of linear regulator when Vref set to 2.1V

As the plot shows, the final output changes to 21V, which is the desired output as it is 10 times the Vref value of 2.1V. The next section combines this linear regulator with the switching power supply circuit to create the combined circuit.

The simulation below is the combined circuit consisting of the switching power supply followed by the linear regulator circuit shown above.

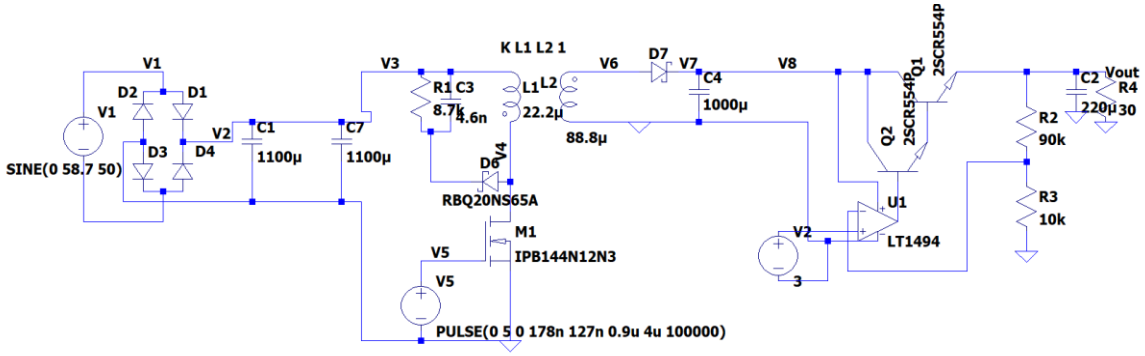

Figure 19: Combined circuit simulation

This circuit has some changes compared to the simulation of just the switching power supply, which is the capacitor at the output of the switching power supply. Due to the power of the op amp supplied from the output of the switching power supply, it is essential that the ripple from the switching power supply be reduced to avoid any issues. The capacitor is increased from 250uF to 1000uF, which allowed the linear regulator to produce a smooth output with no issues. Below is the plot of the output of the switching power supply, or at point V8.

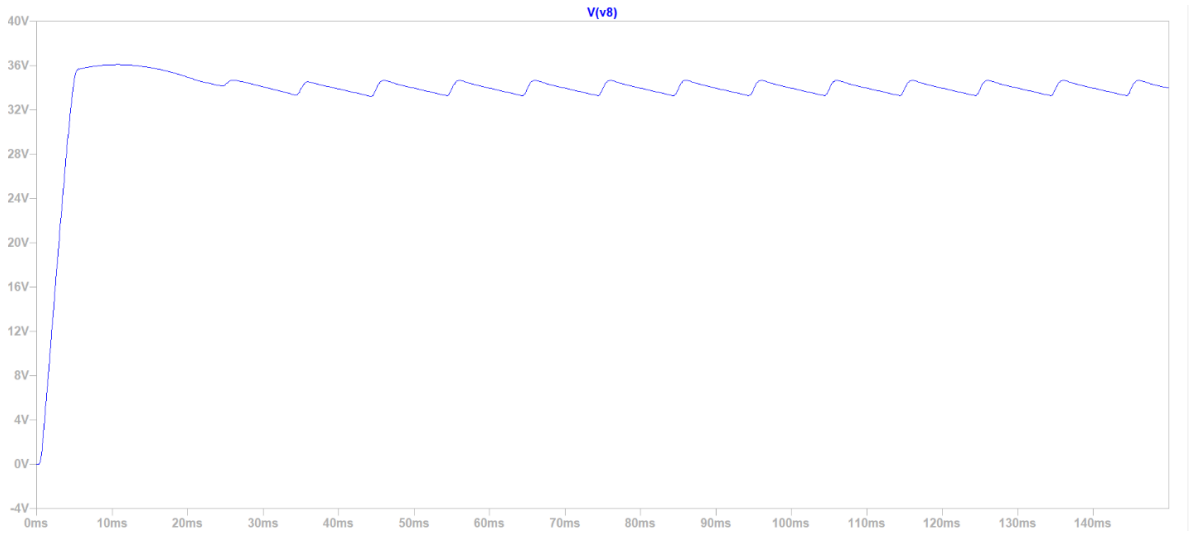

Figure 20: Plot of switching power supply output

The difference between the output of the switching power supply only circuit and this plot is a larger overshoot during the transient phase, but this will not affect the regular operation of the circuit. The overshoot is still not large enough that it does not require any change of components in the circuit. Below is the zoomed in plot along with the value of the ripple.

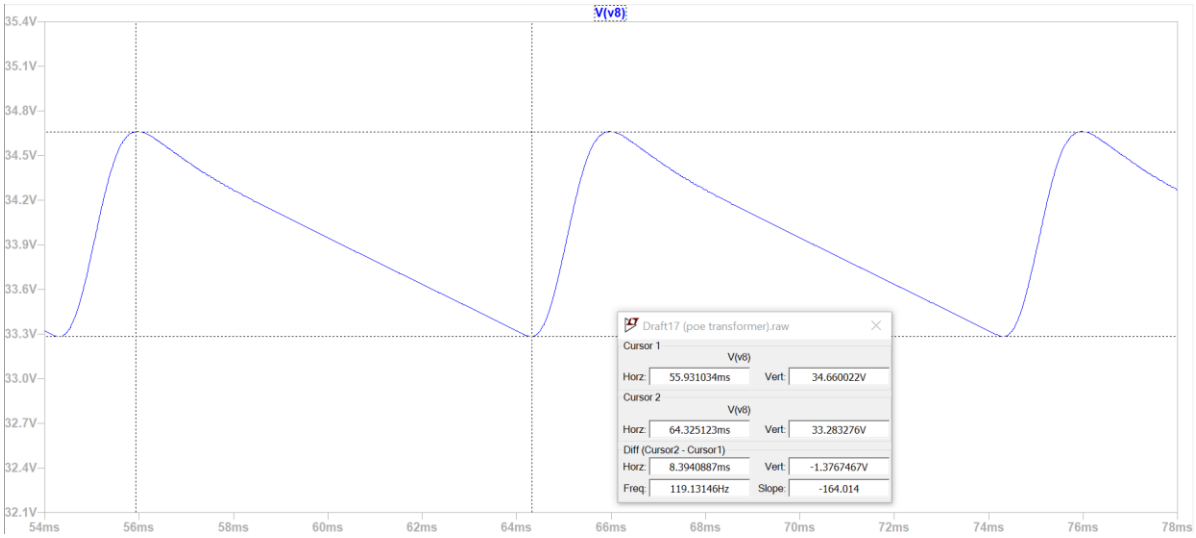

Figure 21: Zoomed in plot of switching power supply output

In this plot, it can be seen that the ripple is 1.38V, which is slightly lower than the ripple from the output of the switching power supply only circuit.

As seen in Figure 36, the final output has a 220uF capacitor. This is to help the closed loop response of the system, where if the load changes, there would be an immediate voltage drop before the system can detect the load change. The capacitor would help reduce the voltage drop before the system adjusts the system to compensate the new load. The next section discusses the result of the combined circuit simulation at various voltages.

The next part will show the result and plot of the combined circuit at 3 different voltage levels, 1V, 15V, 30V, all at 1A. In each step, the duty cycle of the PWM signal is adjusted to reduce the voltage output from the switching power supply. For any output lower than 4V, the switching power supply will remain at 4V due to the minimum voltage of the op amp, and the linear regulator will reduce all the voltage from that point. Below is the plot of the output when the voltage is set to 30V at 1A, using a load resistance of 30Ω.

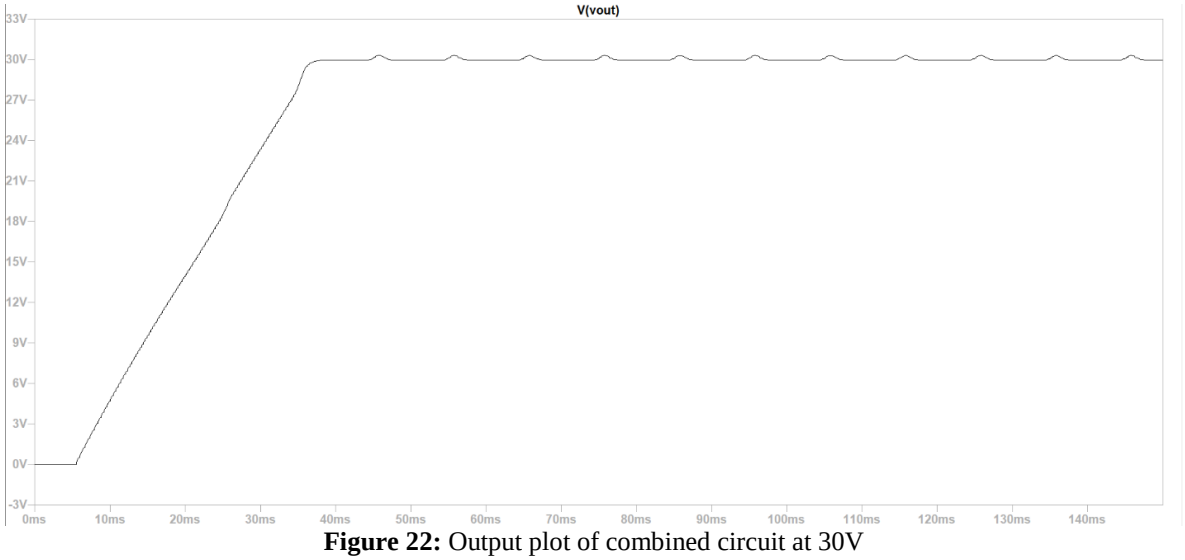

Figure 22: Output plot of combined circuit at 30V

The waveform is shown to be very smooth and has very small ripple, along with no visible overshoot during the transient phase. Below is the zoomed in plot with the values of the waveform.

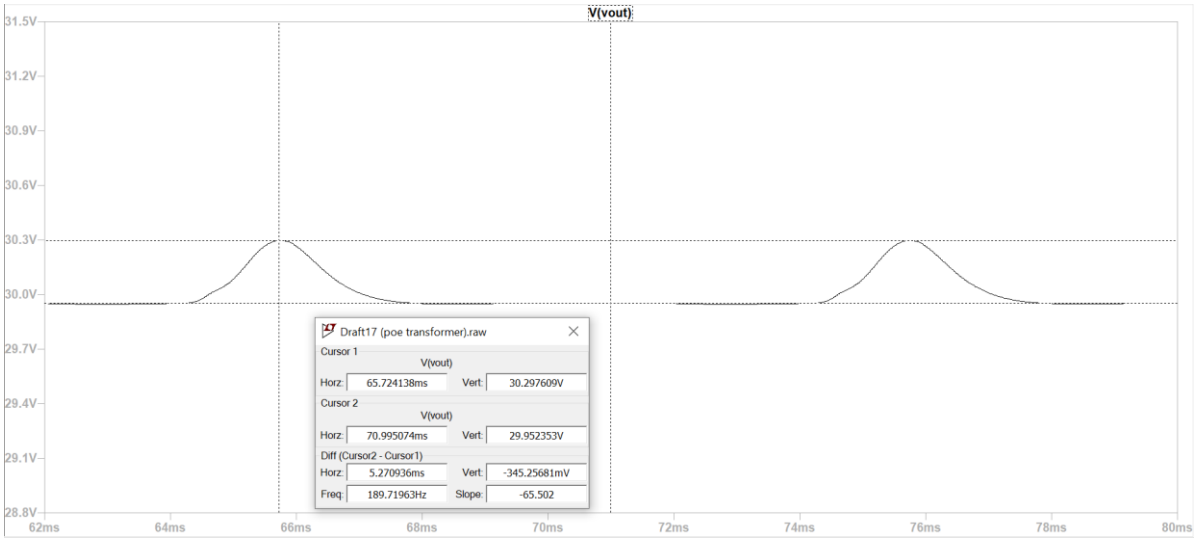

Figure 23: Zoomed in output plot set to 30V

Here it can be seen that the small ripple is only 300mV, which is ideal and does not affect the overall output of the circuit. These small peaks are discussed in the next section of the report. The next figure shows the output plot when set to 15V at 1A, using a 15Ω load.

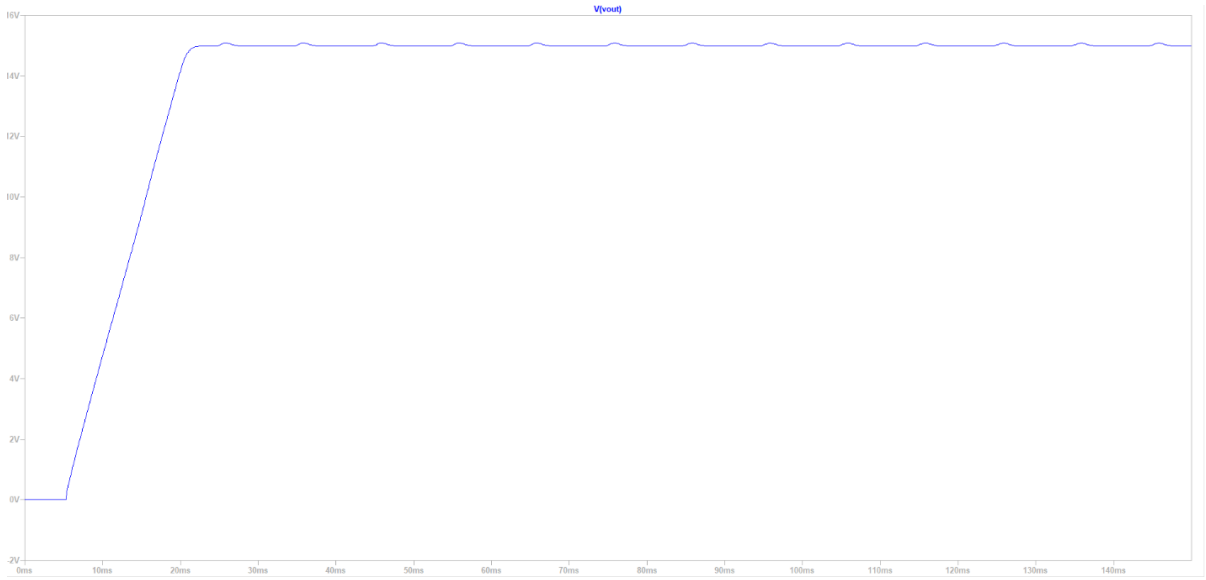

Figure 24: Output plot of combined circuit at 15V

The output, similar to the 30V output, is very smooth with small ripples, and no visible overshoot. The transient phase is shorter and reaches the desired 15V faster. Below is the zoomed in plot of the waveform.

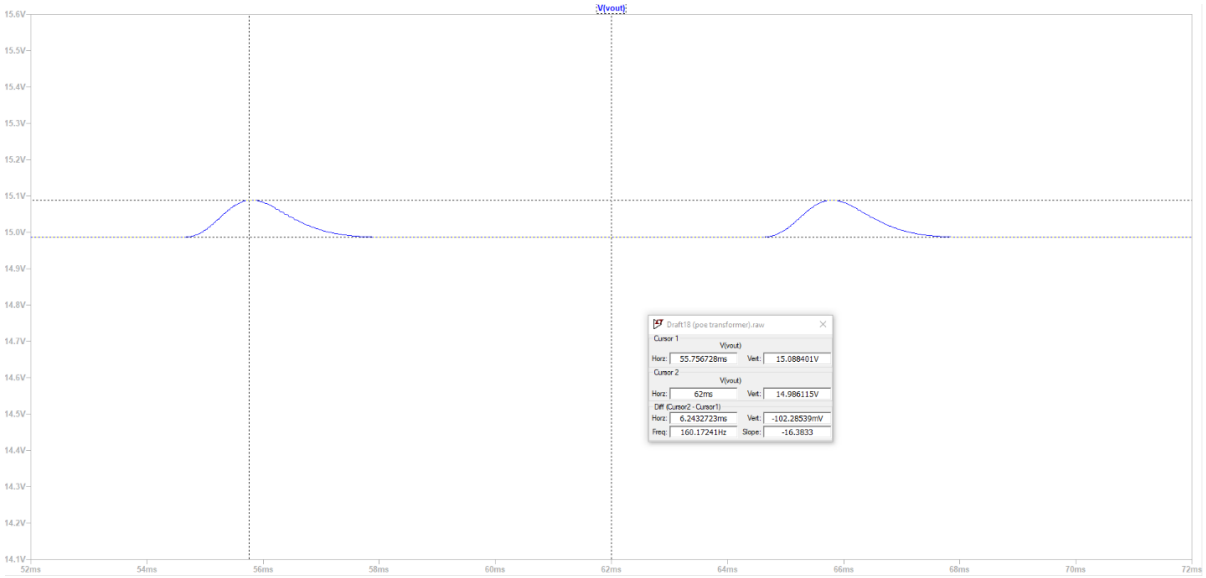

Figure 25: Zoomed in plot of combined circuit at 15V.

The peak of the ripple is 15.08V and the lower value was 14.98V, which shows the circuit is delivering the desired output of 15V. The plot below shows the output at 1V at 1A using a 1Ω resistor.

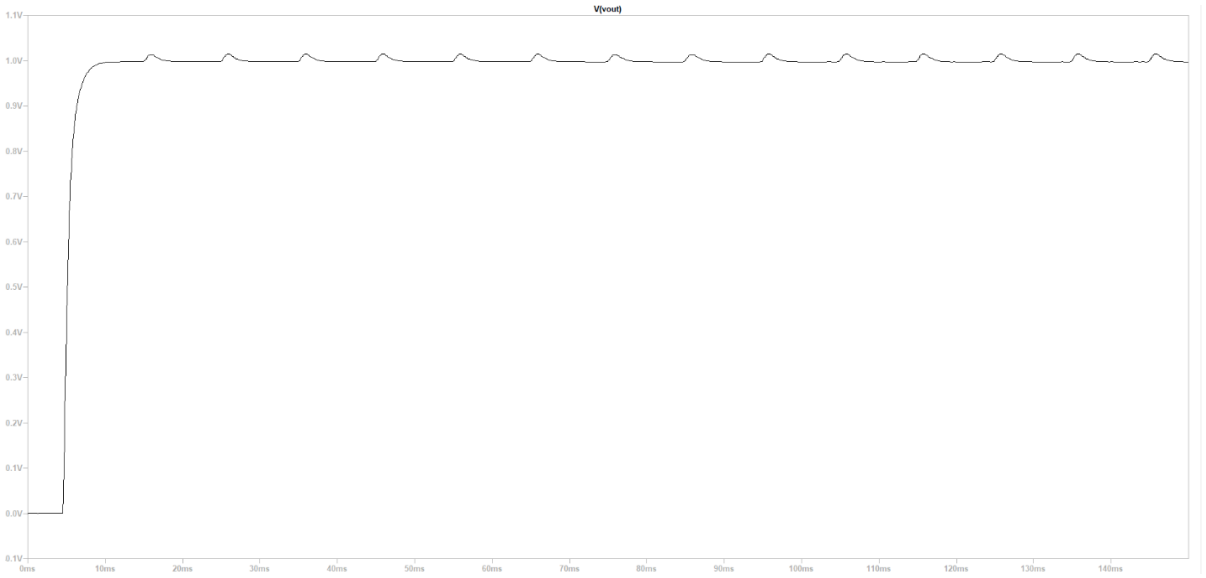

Figure 26: Output plot set to 1V

As the same as the other plots, the desired output of 1V has been achieved, with minimal ripple, and the figure below will show the value of the ripple.

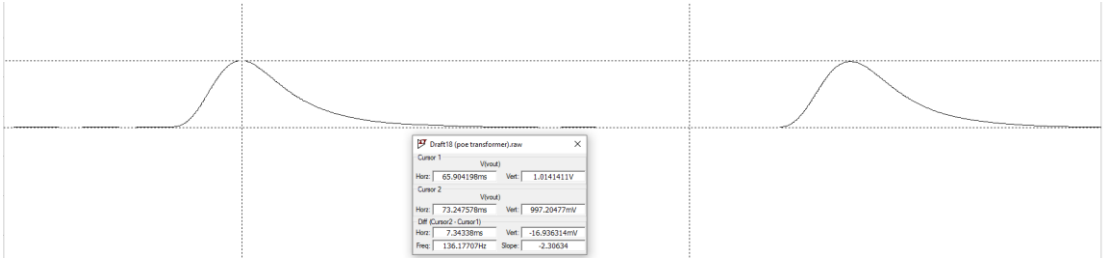

Figure 27: Ripple value from output set to 1V

It can be seen that the ripple is 17mV, which is almost negligible and will not affect the output of the circuit. This proves that at 3 different output values, the circuit performs as desired.

VII. HARDWARE TESTING

The components that were tested were the ADC, DAC, and PWM of the microcontroller, and then the prototype hardware circuits were tested.

The analog to digital converter in the microcontroller needed to be tested to see how accurate the sensor is for use in this project. The testing methodology is by comparing the value received in the microcontroller against the actual value in the ADC pin in different voltage levels. A range of 0-3.0 V was used as that will be the range experienced by the ADC in the actual project. The actual voltage is measured by a digital multimeter connected to the ADC pin and the microcontroller GND pin. Below is the plotted result of the percentage error of the analog to digital converter sensor. The full result is shown in the appendix.

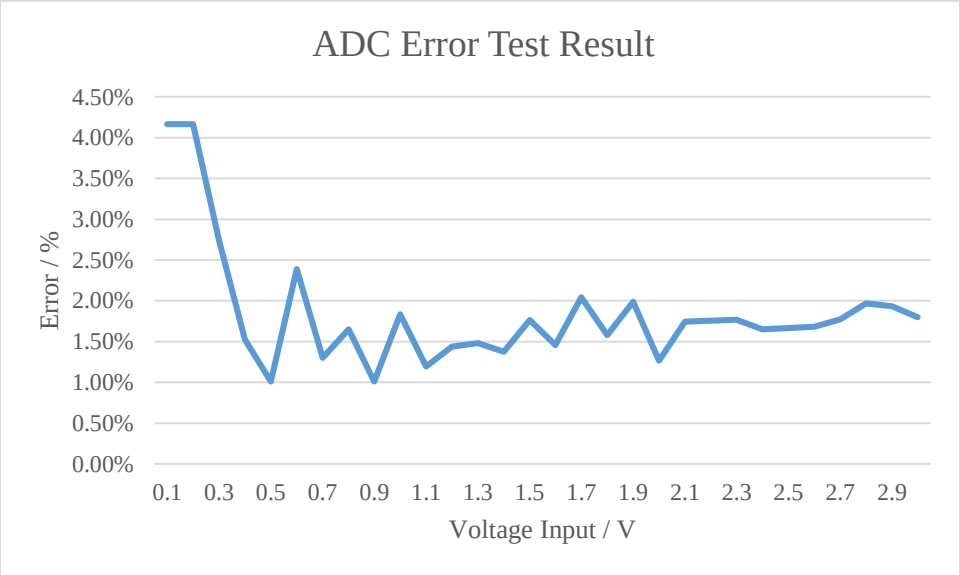

Figure 28: Plot of ADC Error

The results show that the ADC error is low at around 2%. The exception to this is at very low values such as 0.1 and 0.2 V. This is because at low voltages, any small changes in voltage will result in large percentage changes. When the ADC detects a 0.1V input, the actual input is 0.096V, a difference of only 0.004V, which is small enough to not cause any major issues. Hence the ADC in the microcontroller is accurate enough to be used without any adjustments in the software or elsewhere in the system.

As this system uses an external DAC, specifically the MCP4921, it needs to be tested to ensure the result it is giving is accurate. The testing methodology is carried out by measuring the output of the DAC connected directly to a digital multimeter, in reference to the microcontroller GND pin. Below is the plot of the error of the DAC, with the full result shown in the appendix.

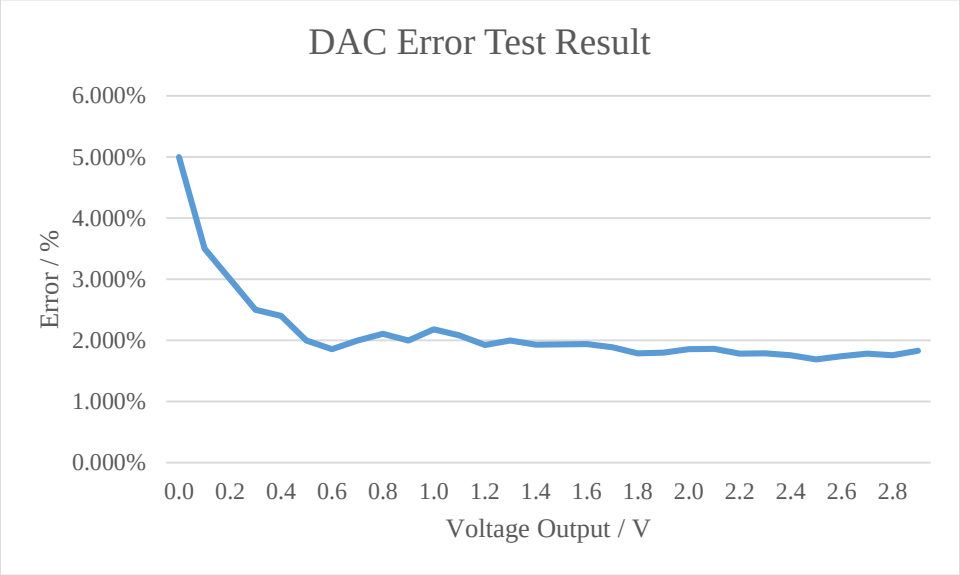

Figure 29: DAC Error result

This plot illustrates that the error is around 2% for all values aside from low values. This is because at low values, any change in voltage will cause a proportionally larger percentage change. For example, when the DAC is programmed to output at 0.1V, it outputs a 0.095V, which is only a 0.005 V difference. This means this DAC has excellent performance and small error, and does not require any adjustment in software.

The PWM is generated by the microcontroller, and such the waveform needs to be analysed to make sure the signal is suitable to be used by the switching regulator circuit. To see how well the microcontroller can output the PWM signal, a 250KHz PWM signal is viewed to the oscilloscope, and at various duty cycle. Below are the oscilloscope outputs.

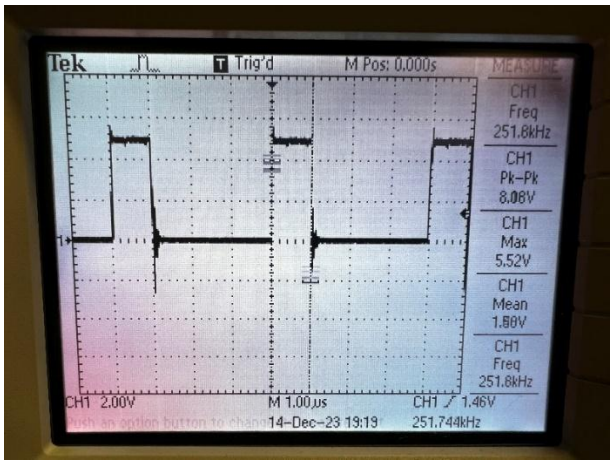

Figure 30: PWM Oscilloscope Output running at 250KHz

Here it can be seen that the microcontroller is capable of outputting a 250KHz PWM signal. Additional testing has shown that the microcontroller can measure at various duty cycles. Therefore, to control the switching power supply, the microcontroller's PWM signal is suitable for the task and does not need any external devices to assist in PWM generation.

The hardware prototype of the switching circuit was built on a Veroboard and using the components selected earlier. Below is the image of the circuit.

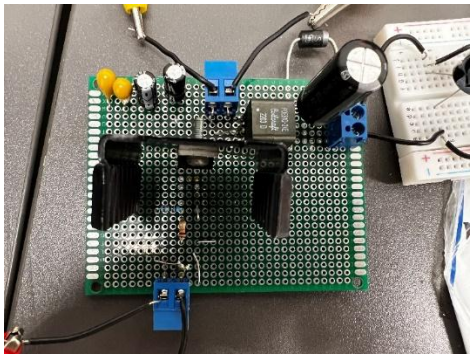

Figure 31: Switching circuit prototype

This prototype includes extra capacitors at the input and output to reduce any noise that can be generated in the system or picked up from the environment.

This prototype is tested by changing the duty cycle and measuring the voltage output. There is a limitation with the function generator that limits the minimum duty cycle to 20%. This test is measured by connecting an oscilloscope output to the output of the circuit. Below are the results.

Table 2: Switching power supply testing

Duty cycle / %	Voltage output / V
20	17.0
25	20.2
30	22.6
35	25.8
40	28.1

This proves the switching regulator circuit is functional and can output at various voltages. The next section will show the linear regulator circuit and show the results from testing.

The hardware prototype of the linear circuit was built using the components selected and soldered together in a Veroboard. A large heatsink is attached to the transistor to prevent the transistor from overheating due to the large current that will flow through the system. Below is the image of the prototype circuit

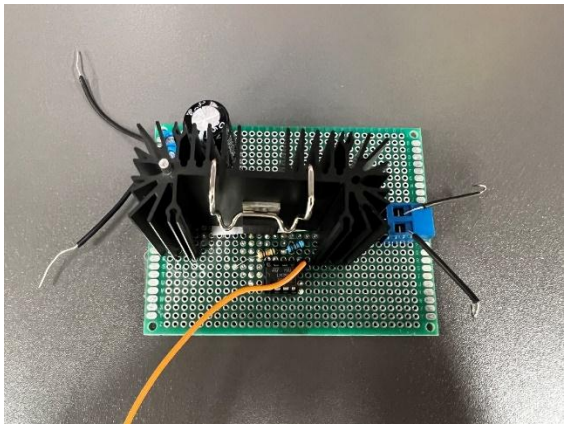

Figure 33: Linear regulator circuit prototype

To see how well the linear power supply circuit performs, it was attached to a 30Ω load using 3 high power resistors in series, and then a digital multimeter was connected in parallel to measure the voltage. In this test, it was discovered that below 10V, the error was a voltage increase compared to the desired voltage, while when outputting above 10V, the error was a voltage decrease compared to the desired voltage. Therefore, the calculation to derive the error values were different at above and below 10V. Below is the plot of the error in percentage against the voltage output.

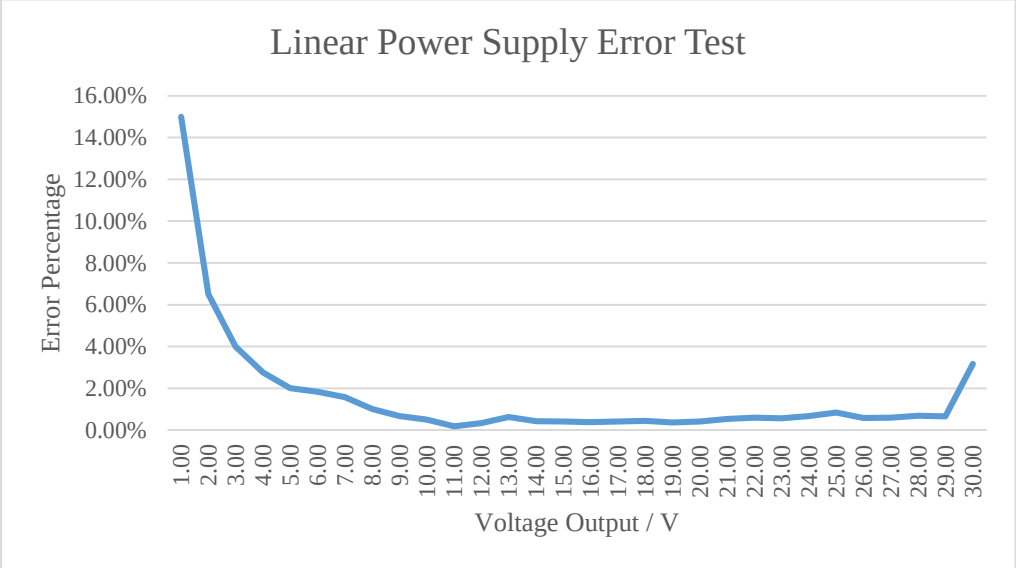

Figure 34: Linear Power Supply Error test

From the plot, it can be seen that aside from very low values and high values, the error remained very low at around less than 1%. The large error at the lowest values is because at low voltages, any small change in voltage will result in large percentage change, as with the other error tests. At 1V, the output was 1.15 V, which is still close enough to the actual output.

A load regulation test is also performed for this circuit. For this test, only 3 voltage outputs will be tested, at 0V, 15V and at 30V. Below are the tests with no load.

Table 3: No load results for linear power supply

Programmed voltage output / V	Actual Voltage Output / V
0	0.179
15	15.270
30	29.840

Using the load regulation formula shown below:

$$Load\ regulation = \frac{Vnl - Vfl}{Vfl} * 100\% \quad (29)$$

The load regulation can be calculated, the result of which is shown below:

Table 4: Load regulation table for linear power supply

Programmed voltage output / V	Load regulation
0	0%
15	2.2%
30	2.72%

This is excellent load regulation as there is very little change between the voltage during full load and no-load scenarios.

Once the 2 circuits have been tested, they are combined in order to see the output from both circuits. Below is the image of both prototypes connected together.

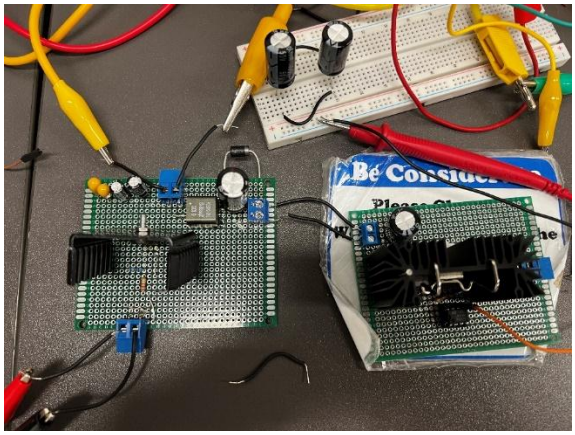

Figure 35: Combined circuit prototype

The output from the oscilloscope is shown below. This shows the output at 22.8V, where it can be seen that no noise is present at the output.

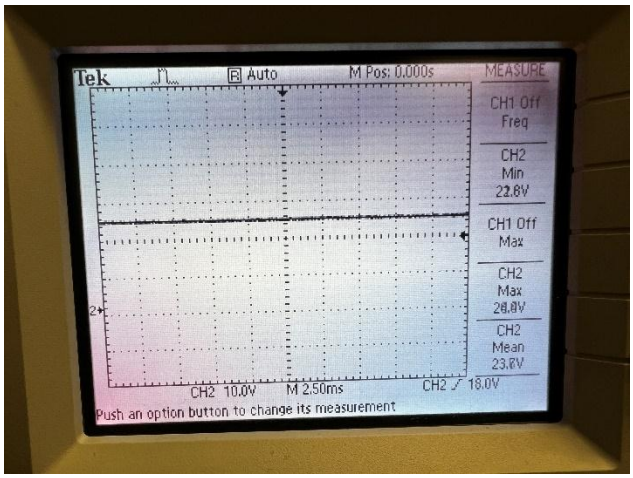

Figure 36: Combined circuit oscilloscope output

This output shows that the system is functioning and can perform output within the output range.

Below is the load regulation calculation for the combined circuit at 3 different voltage outputs, 4V, 11V, and 22V.

Table 5: Load regulation table for combined circuit

no load output / V	full load / V	load regulation
4.2	4	5%
11.9	11.6	2.58%
22.8	22.6	0.88%

This shows the combined circuit prototype has excellent load regulation, and performs well.

The microcontroller was implemented and was functioning correctly. It can correctly control the linear power supply circuit with no issues using the external DAC, and can receive the values from the ADC pin of the microcontroller. It can also correctly output the PWM signal at the desired frequency of 250kHz and at different duty cycles. The DAC was functioning correctly using the SPI interface. Both the ADC and DAC were tested to make sure they are accurate, and as shown in the earlier sections, they are accurate and do not require any adjustments. The microcontroller also functioned correctly according to the software flowchart defined in chapter 7.

VIII. DISCUSSION

The switching regulator circuit functioned and provided a noisy output, but as shown earlier does have variable output according to the duty cycle. The output changes are not as granular as the simulations. This is because of the amount of noise generated in the entire circuit and due to the surroundings. Before the capacitors were added, the circuit performed much more erratically with far more noise, suggesting that a lot of the noise was from external sources. This included the wires, such as the crocodile clips needed to connect to the power supply, and external wires needed to connect to the load.

The linear regulator circuit [54-62] also functioned correctly, providing a smooth output DC output and with little error to the desired output. The feedback system with the op-amp and resistors performed as intended, which contributed to the very small error and near ideal output. External factors such as loss in the wires between the circuit and the load would be the only voltage drop when measuring the voltage at the load.

When the circuit was combined, the output was desired. The noise caused by the switching power supply was eliminated, and the combined circuit [63-71] performed as intended. The output load received the correct output voltage and close to the output current of 1A. This meant the prototype was functional and working as intended.

IX. CONCLUSION

In conclusion, this project presents a new type of power supply [72-76] that combines both a more efficient switching regulator and a ripple free linear regulator to create a hybrid version that has benefits from both types of power supply. The prototype was far smaller and more compact than the usual power supplies, fitting on the size of 3 small PCBs. This project due to its smaller size and weight can create new use cases such as in a portable vehicle or when a device that requires a power supply can be carried to new places without much hassle. The improved efficiency also means on portable devices such as a battery, it can last longer as compared to a normal linear power supply. This device could create new use cases and is a starting point for further development and refinement.

The prototype hardware for both the switching and linear regulator circuits was built, and functioned with control for multiple output levels. The combined circuit functions and can output to a load. The linear regulator circuit performed exceptionally well, and was able to be controlled by the microcontroller at a very granular level.

The microcontroller system along with the software developed performed up to expectation, with the software running with no issues and at proper speed. The software could generate a PWM signal, take a voltage value from the ADC, generate a voltage value by sending a signal to the external DAC through the SPI interface, store the current programmed voltage value, and display to the LCD to the user all in one cycle. The microcontroller had no slowdowns when performing this task and consumed minimal power despite all the functionality it can perform.

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