FLEXUSB Charger

6.101 Final Project Report

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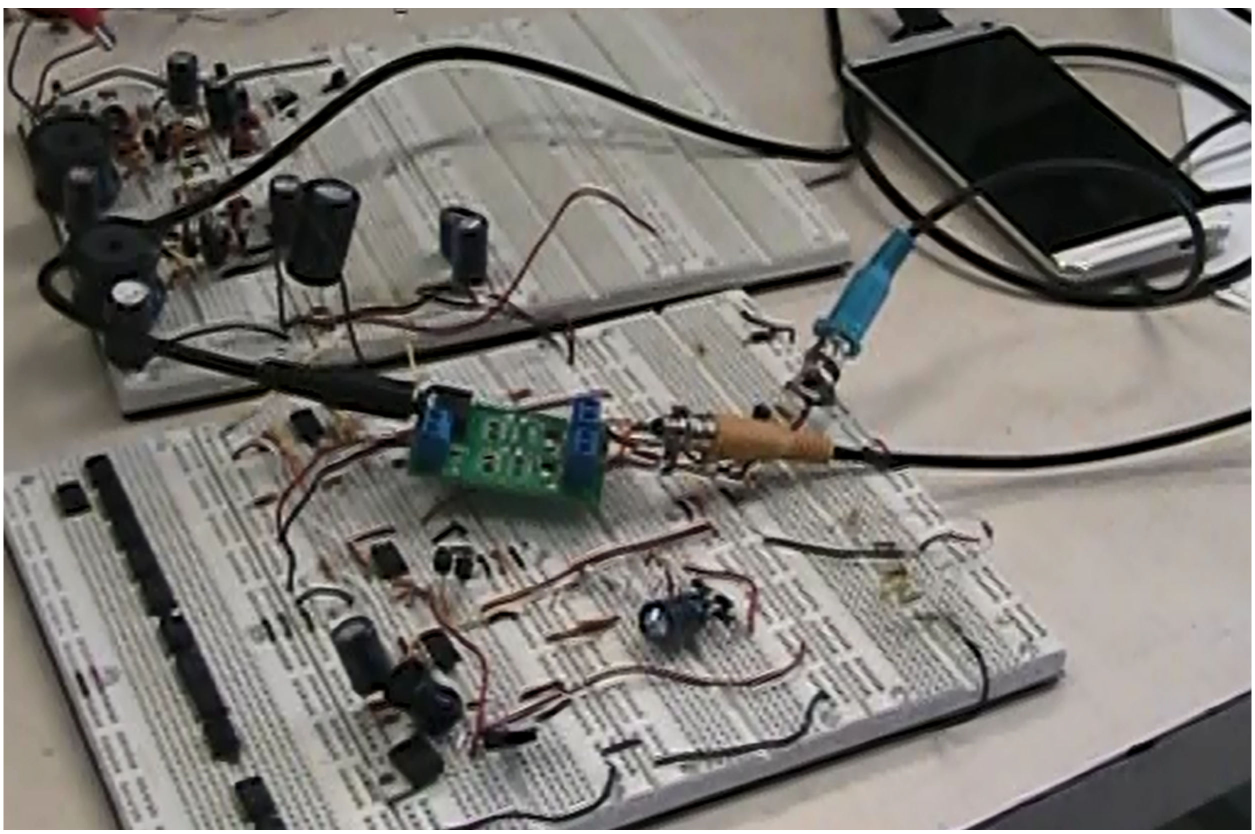

Abstract

Our goal in this project was to design a USB charger that could run off of any common battery from at least 1.5V to 12V. In tackling this challenge, we built a boost-buck converter in a two-stage topology (boost into buck). Our final completed system was capable of being powered from voltage sources ranging from 1.4 to 15 volts, and was capable of charging a phone using voltages ranging from 1.9 to 15 volts. The system could not successfully act as a charger using a single 1.5 volt battery unfortunately due to the power requirements and the limitations of our chosen control circuitry. However, when using two or more 1.5 volt batteries in series or another voltage source as specified above the system performed excellently with a minimum operating efficiency of 60% while charging an iPhone.

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Overall Design - Alex and Fiona

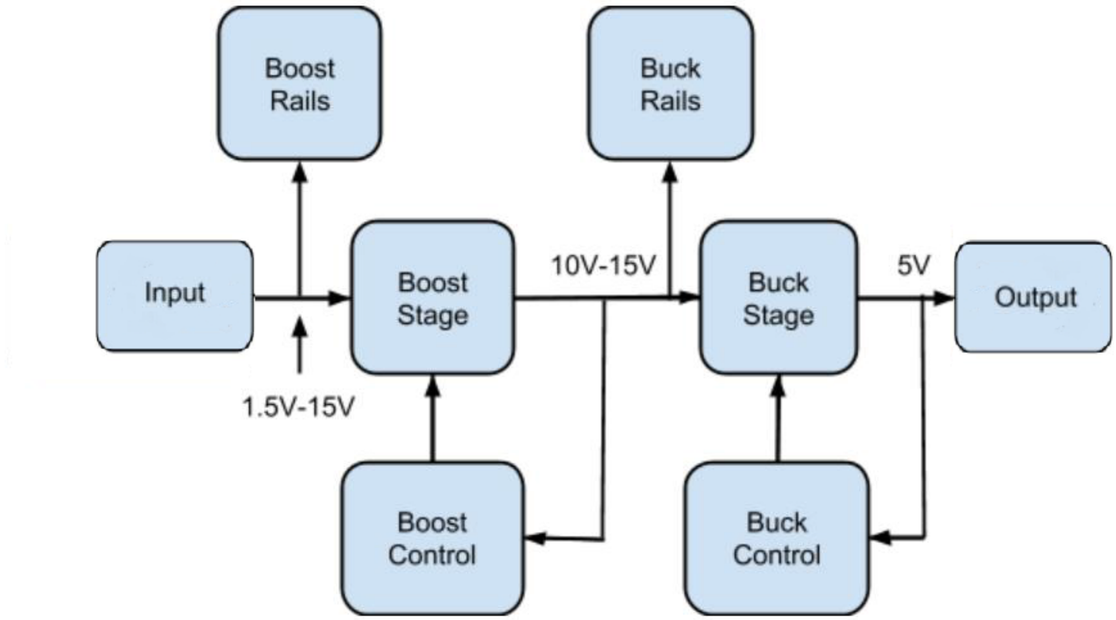


Fig. 1 System Block Diagram

In order to accomplish our goal of creating an efficient USB charger from varying inputs, we settled upon a boost-buck cascaded topology. This topology offered the promise of high efficiency, which is essential in battery powered applications such as ours, and a high degree of modularity, allowing us to work independently and rapidly. Our completed system was capable of taking DC inputs, varying from as low as 1.4 volts to 15 volts, along with AC wall voltages, and converting them to a steady USB standard 5 volts. So long as the DC input voltages were greater than 2 volts it was also able to sustain the 5 volt output even with a current draw of 500 milliamps, such as when charging a cell phone. These feats were accomplished with an overall system efficiency of 60% and higher depending upon the input and load.

The system can be thought of in two major partitions, the initial boost stage that either allows the passing of high voltage inputs, greater than 10 volts, or utilizes its boost capabilities to increase lower voltages to a minimum of 10 volts, and the buck stage which takes these heightened voltage levels and converts them to a steady 5 volt output.

The boost stage is powered solely by the voltage input provided and as such all of its components function at 1.5 volts and are capable of withstanding at least 15 volts.

Utilizing feedback from its output and input the boost stage is capable of deactivating itself when it does not need to increase the output voltage any longer, increasing efficiency and easing voltage output control. For instance, if the input voltage is higher than the 10 volt minimum output, it is simply allowed to pass through to the output through the use of control mosfets. If it is lower though than 10 volts, it is boosted using a conventional boost topology and held at a stable output of 10 volts by the control system which monitors the output.

The buck converter takes the voltage output of the boost stage, from 10 - 15 volts, and outputs a steady 5 volts with a ripple below 0.25 volts. The buck stage is being powered at a higher voltages than the boost stage, 10 volts or more, as it follows the boost and uses the boosts output for power rather than the input voltage. To control the buck stage, the output voltage of the converter is compared to a reference voltage and the input bucked until a 5 volt steady output is achieved.

Boost Stage - Alex

The Boost Stage constitutes the front end of the USBFlex Charger system and is responsible for taking in the wide array of possible input voltages (1.4-15 VDC, 120 VAC RMS) and compressing them into a more narrow window (10-15 VDC) for the Buck Stage. The Boost Stage itself is comprised of four modules that work together to accomplish this goal, the Boost Module, Input Module, Rails Module, and Control Module.

Boost Module

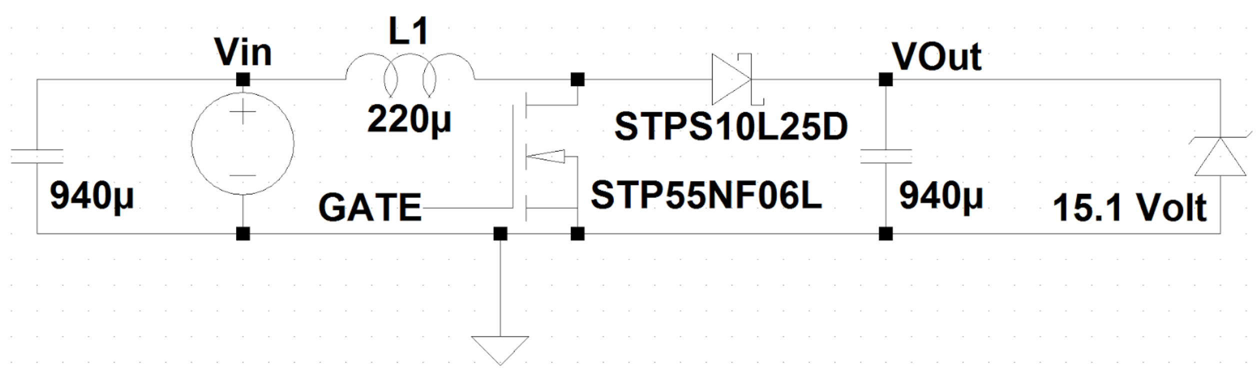


Fig. 2 Boost Module Schematic

The Boost Module is the primary module of the Boost Stage and is responsible for converting DC voltages between 1.4 and 10 volts to 10 volts. In addition, for higher input voltages, the Boost Module passes these voltages directly on to the Buck Stage nearly unaltered. These functions are done utilizing a normal boost converter topology consisting of a 220 uH inductor, a power mosfet, a diode and capacitor.

Under normal operation in this topology, currents are built up in the inductor by turning on the power mosfet. When the power mosfet is activated, a near short is created between the output side of the inductor and ground. The result is that a near constant voltage is applied across the inductor, which results in a linearly increasing current within the inductor itself. Then, with a current built up in the inductor, the power mosfet is turned off. Having lost the mosfet as a potential current path, the current built up in the inductor instead flows through the diode, charging the capacitor on the output to a voltage higher than that of the input. With the voltage across the inductor now negative, current will begin to decrease. In order to maintain the output voltage at a higher level, the mosfet is continually switched on and off resulting in an output voltage approximately equal to the input voltage times $\frac{1}{(1-D)}$ where D is the duty cycle of the switching mosfet. This duty cycle is provided by the Control Module.

All of the parts within the Boost Module were carefully chosen in order carry out all the specifications of the Boost Stage successfully but also in an efficient manner as all of the power delivered to the Buck Stage must pass through this module. The power mosfet chosen possesses a threshold voltage around 1.7 volts allowing it to be turned fully on by the rail voltages generated in the Rails Module. In addition, it has a very low on resistance on the order of tens of milliohms minimizing power dissipation when it is providing a path to ground.

Most of the power dissipated in this module is within the inductor and diode as current is almost constantly flowing through both of these components. The inductor was chosen for its high saturation current of around 8.7 amps as might be needed for brief instances in the Boost Module at startup. It also possessed a series resistance of approximately 80 milliohms which contributed to some loss of power efficiency. The diode was chosen for its low forward voltage drop and ability to handle the current needs of the module. At typical currents, the diode possessed a forward voltage drop of approximately 0.3 volts, reducing power wasted as compared to other common diodes.

The other components seen in the Boost Module are the output capacitor along with a resistor and a zener diode. The capacitor was chosen in order to handle the current needs of the Buck Stage without undergoing significant voltage changes. As such, larger capacitors would be more beneficial as they would minimize the impact of sudden current discharges on voltage. The output resistor is in place to bring down the output voltage if there is no load and the capacitors become overcharged. The zener diode acts to ensure that the output voltage never exceeds 15 volts as that could potentially be beyond the voltage handling capabilities of the Buck Stage.

Input Module

The Input Module is the simplest of the modules and is used to both rectify the voltage, should it be from a wall outlet, and to transform the input voltage into two reference voltages to be used in the Control Module and Rails Module. The conversion of AC wall voltages into DC is carried out by a transformer that is plugged directly into a wall outlet and whose secondary voltage is made DC by a common bridge rectifier set-up and capacitor. In order to produce the reference voltages for use in the Control and Rails Modules, the input voltage is applied to two voltage dividers producing reference voltages equal to 12% and 25% of the input voltage respectively. The components in the Input Module will be visible in the schematics of the other modules.

Rails Module

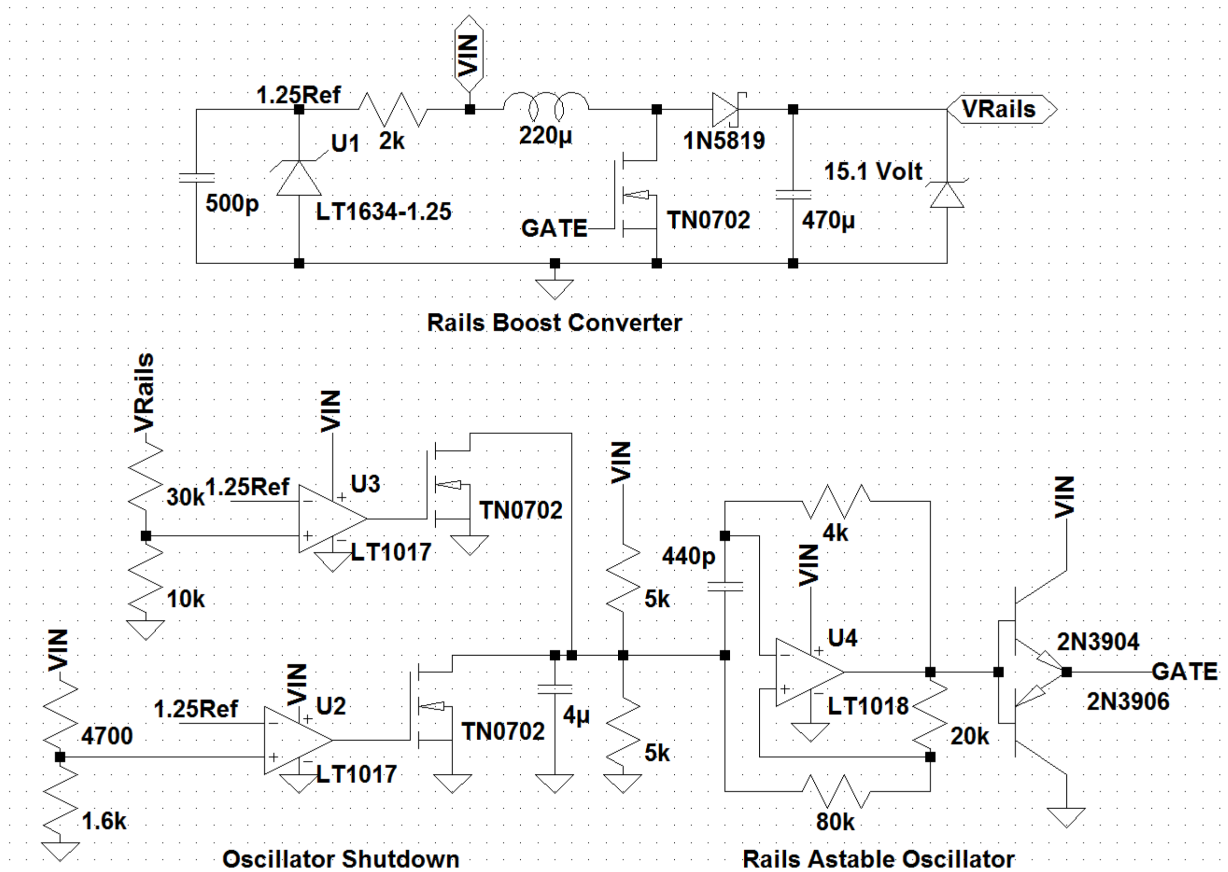


Fig. 3 Rails Module Schematic

The Rails Module works to take the lowest end of possible input voltages and convert them into higher voltages that will power the Control Module. This module was necessary as input voltages could be as low as 1.4 volts. Controlling the mosfet in the Boost Module proved to be too difficult with input voltages so low as the gate capacitance of the mosfet as well as its threshold voltage became increasingly significant factors in overall performance. With the Rails Module in place, however, the Control Module can depend on operating voltages of at least 3 volts, giving it much more flexibility.

To create these higher voltages, the Rails Module itself consists of another boost converter running open loop, almost identical to that of the boost converter in the Boost Module. The main differences between the two are that they utilize different switching mosfets and the control circuitry for the Rails Module is less complicated and attempts to produce a 5 volt output rather than a 10 volt output as in the Boost Module.

The control circuitry in the Rails Module is composed of two Linear IC comparators. One of the IC's, the LT1018 works as an astable oscillator. This is accomplished by creating a virtual ground equal to half of the input voltage since no negative supply is available and oscillating around said virtual ground. When running, it achieves a frequency of approximately 70 KHz and generates a rough square wave with a duty cycle around 50%. This square wave is used as the input to two complementary BJT's in a push-pull configuration that then act as a driver for the switching mosfet in the boost converter. This driver is needed as the LT1018 is not capable of sinking or sourcing enough current to both act as an oscillator and charge/discharge the gate of the switching mosfet. By driving the gate at a duty cycle of 50%, the Rails Module outputs a voltage approximately twice that of the input voltage for the Controls Module to use.

In addition to the IC acting as the oscillator, an LT1017 IC is also present and serves to monitor the input and output voltages in order to deactivate the oscillator should either becomes too high. A 1.25 volt reference voltage is created using a Linear voltage shunt in series with a 1k resistor at the input. This reference voltage is input into both of the comparator's V- terminals. The input and output reference voltages come from two voltage dividers and enter into the two V+ terminals of the comparator. The input reference voltage is produced in the Input Module and is equal to approximately 25% of the input voltage. The output reference voltage is produced in the same manner within the Rails Module and is also equal to approximately 25% of the Rails Module output voltage.

When either of these reference voltages exceed 1.25 volts, the comparator will activate a mosfet, connected between the oscillator's virtual ground and actual ground. This effectively shorts the virtual ground to actual ground and ceases oscillations. Importantly, it also results in the output of the oscillator going to ground as it tries to go below the virtual ground. As such, the gate of the switching mosfet is also brought to ground turning it into an open as opposed to a short when the oscillator is deactivated. Should the conditions that led to the deactivation of the oscillator halt, the comparator would deactivate the mosfets acting to ground the virtual ground and the oscillator would continue with normal operation.

Control Module

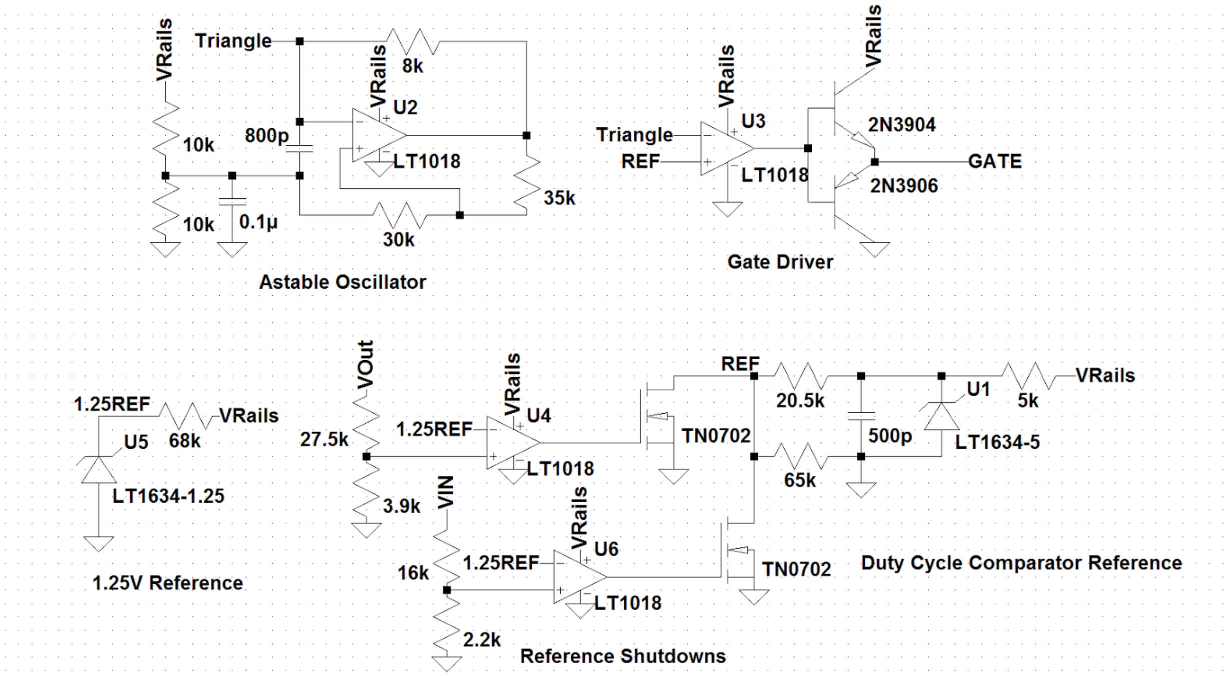


Fig. 4 Control Module Schematic

The Control Module for the Boost Stage is very similar to that of the control circuitry within the Rails Module. In both cases, an LT1018 is acting as an astable oscillator and the driving circuitry can be shut down based off of the input and output voltages. In addition, the driver for the switching mosfet is again a push-pull complementary BJT amplifier. In this case though, the duty cycle is varied based off of the input voltage as well which necessitates additional circuitry. Also, the operating frequency is instead approximately 39 KHz and the output is controlled to be equal to 10 volts as opposed to 5 volts so long as input voltages do not exceed approximately 10.4 volts.

In order to make an input voltage dependent duty cycle to control the output voltage, the triangle wave present at the capacitor in the astable oscillator is taken as output rather than the square wave present at the output of the comparator. This triangle wave is then passed into a comparator along with an input dependent reference voltage. The output of the comparator is then a square wave whose duty cycle depends on the height of the reference voltage relative to the height of the square wave.

This is a very common method of varying duty cycles in switching converters but ran into a series of challenges in this particular implementation. For instance, the amplitude of the triangle wave is dependent upon the rail voltage used to power the comparator in the astable oscillator. As such, both its amplitude and the magnitude of the input reference voltage both initially rose with increasing input voltages which resulted in very ineffective duty cycle control.

To better control the duty cycle two important changes were made to the circuit. For one, the voltage powering the astable oscillator comes from the Rails Module rather than the input voltage directly. As such, for lower input voltages, the amplitude of the triangle wave remains relatively fixed since the Rails Module attempts to maintain a 5 volt output at low levels. At the same time the reference voltage is also partially based off of the rails voltage, meaning at input voltages below 5 volts we have a fixed duty cycle of approximately 80-85%.

The reference voltage is only partially based off of the rails voltage because right before the voltage divider a 5 volt shunt is placed. This means that when input voltages exceed 5 volts and begin to increase the rail voltages, the triangle wave amplitude will increase but the reference voltage will remain constant. So for increasing voltages above 5 volts introduced into the system, the duty cycle decreases proportionally.

Unfortunately, the proportionality is not exactly right in order to obtain the ideal duty cycle but it does work to limit having too high of a duty cycle for large input voltages. To handle this, feedback is again used to shut down the driving circuitry when the output voltage becomes too high, this time by driving the reference input of the duty cycle comparator to ground rather than by halting oscillations. Errors in duty cycle are always on the side of higher duty cycle meaning that this control system should always be able to manage the output voltage given an appropriate input voltage. Effectively, the average duty cycle, including time with the oscillator off, comes to equal the ideal duty cycle leading to the desired 10 volt output. The negative consequences of this method of operation are that the output voltage has a very noticeable ripple when high input voltages are used, but this ripple was never seen to be enough to affect operation of the system.

Results

Combining all of the aforementioned modules together proved to be very simple due to the level of compartmentalization and the minimal number of interconnects needed. Under testing and operation, all modules performed as expected and followed the models in simulation to an very high degree of accuracy. In simulation, the Boost Stage was found to have a power efficiency of 85% when powered by a 2 volt source and driving a 30 ohm load, and higher levels of efficiency with higher input voltages. In reality, the system demonstrated an efficiency of around 81% with an input voltage of 2 volts while driving a 32 ohm load and again higher efficiencies with higher input voltages as expected.

Testing - Alex

In the Boost Stage, all of the various modules were capable of being tested independently which greatly eased assembly and debugging when breadboarding began. Again the Input Module proved the easiest to test as it simply consisted of the rectifier and voltage references. These were tested by measuring the voltages across the input and comparing them to the source voltage to make sure they were the same. The voltage dividers were tested by measuring their reference voltages and ensuring they were the correct fraction of the input voltage.

The Rails Module was constructed second as it was necessary for the operation of the Control Module and Boost Module. To test the Rails Module it was built in functional units, such as the astable oscillator and oscillator shutdowns and these were tested individually before being connected. Frequency, amplitude and shape of the square wave at the oscillator's output were measured at various input voltages and confirmed to match closely to those found in simulation. Next, the oscillator shutdowns were tested by applying known voltages to the negative inputs and making sure that the comparators tripped at the desired voltages. The shutdowns were then connected to the oscillator and tested again to ensure the oscillator did actually shut down when the input and output comparators were tripped.

Next the BJT push-pull driver was added to the oscillator and its output was checked as well to ensure that it was successfully following the oscillator's square wave. With all of the control circuitry working, the boost converter portion of the Rails Module was then built up and connected to the control circuitry. Using a current limiting voltage source, it was then tested by sweeping over the full range of possible input voltages and ensuring that the output voltages were as expected. Once this was confirmed the Rails Module was fully tested.

Following the Rails Module, the Control Module was constructed again in a piecewise fashion following the example of the Rails Module. In the same manner, the astable oscillator was built and its triangle wave output was measured to confirm it matched the simulation. Then the comparator shutdowns were put in place and tested in the same manner as in the Rails Module. All of this was done with the Control Module being powered by the rail voltage supplied by the Rails Module.

With all of the circuitry like that of the Rails Module built, the next step was to build the duty cycle controller. Using the triangle wave produced by the astable oscillator and a voltage from a voltage source, the comparator was tested to ensure that a square wave with changing duty cycle would be produced by changing the input from the voltage source. Finally, the input voltage reference circuitry was built and also sent to the duty cycle controller while the output square wave was sent to the BJT push-pull amplifier and the duty cycle at its output was monitored over varying input voltages to ensure desired performance, completing the testing of the Control Module.

After all other modules were successfully built and tested, the Boost Module was put together and connected to the rest of the Modules. While wearing safety glasses and utilizing a current limited voltage source, the entire Boost Stage was then tested over the full range of input voltages and various loads, ensuring a steady 10 volt output or higher to complete the testing of the Boost Stage.

Design Experience - Alex

Designing and constructing the Boost Stage of this system was an incredibly educational and interesting experience. Prior to this project, I had had no experience working with the design of power electronics or switching converters and thought that diving in would be a great way to further my understanding. This proved to be a great decision as I don't think I would have been able to learn as much as I have by reading or doing more theoretical problems.

In coming up with the initial design for the Boost Stage I read many very informative application notes and design guides from TI, Maxim Integrated and other companies very experienced in the design of these devices. From these notes and guides I was able to work with and understand many of the formulas governing switching converters and avoided many potential pitfalls early on in the process. I also developed a good feel for common values found in switching regulators and learned a lot about how to use LTSpice to simulate their operation.

Beyond the general insight found in online resources, this project also drew upon many of my experiences in 6.101. Many of the smaller subcircuits within my modules are modified versions of labs we performed, such as the astable oscillators. In addition, when considering how to drive the switching mosfets I knew to keep in mind the various current and voltage limitations of the driving devices I had chosen. The project provided a strong incentive to fully understand many of the concepts and designs covered in 6.101 and certainly helped me to do so through a great deal of practice.

Looking back on the process I am certainly happy with the final product but see many areas that could be improved upon. Having talked with Dan Weber and Professor Hom, there are certain assemblies I chose that could be easily modified such as the push-pull drivers I used. I settled upon the push-pull drivers as we had often used them in amplifier systems and as such I knew they would be able to handle driving the switching mosfets, however, using them in an inverting configuration would have resulted in better swing on the mosfet gates than what is obtained in the push-pull configuration. Also, given more time, I think I would have tried to complete the project without the use of any IC's as suggested by Joe Sousa and Professor Hom.

While there are many more areas that I could have improved upon greatly, such as the control circuitry and power efficiency, I think these would have required a greater degree of familiarity with the general workings of switching regulators prior to starting the design process. This new knowledge will certainly come in handy in future projects and I am very glad I had the chance to work on such an interesting, complex system.

Buck Stage - Fiona

The buck stage is the second half of the power converter. It takes the output of 10-15V from the boost stage and bucks the voltage to 5V at the USB standard of +/- 0.25V of ripple and average current of 500mA with a max current of 1.5A. The buck stage is about 75% efficient owing in large part to losses in generating the rails and reference voltages. The buck stage has four main parts: rails, buck, control, output.

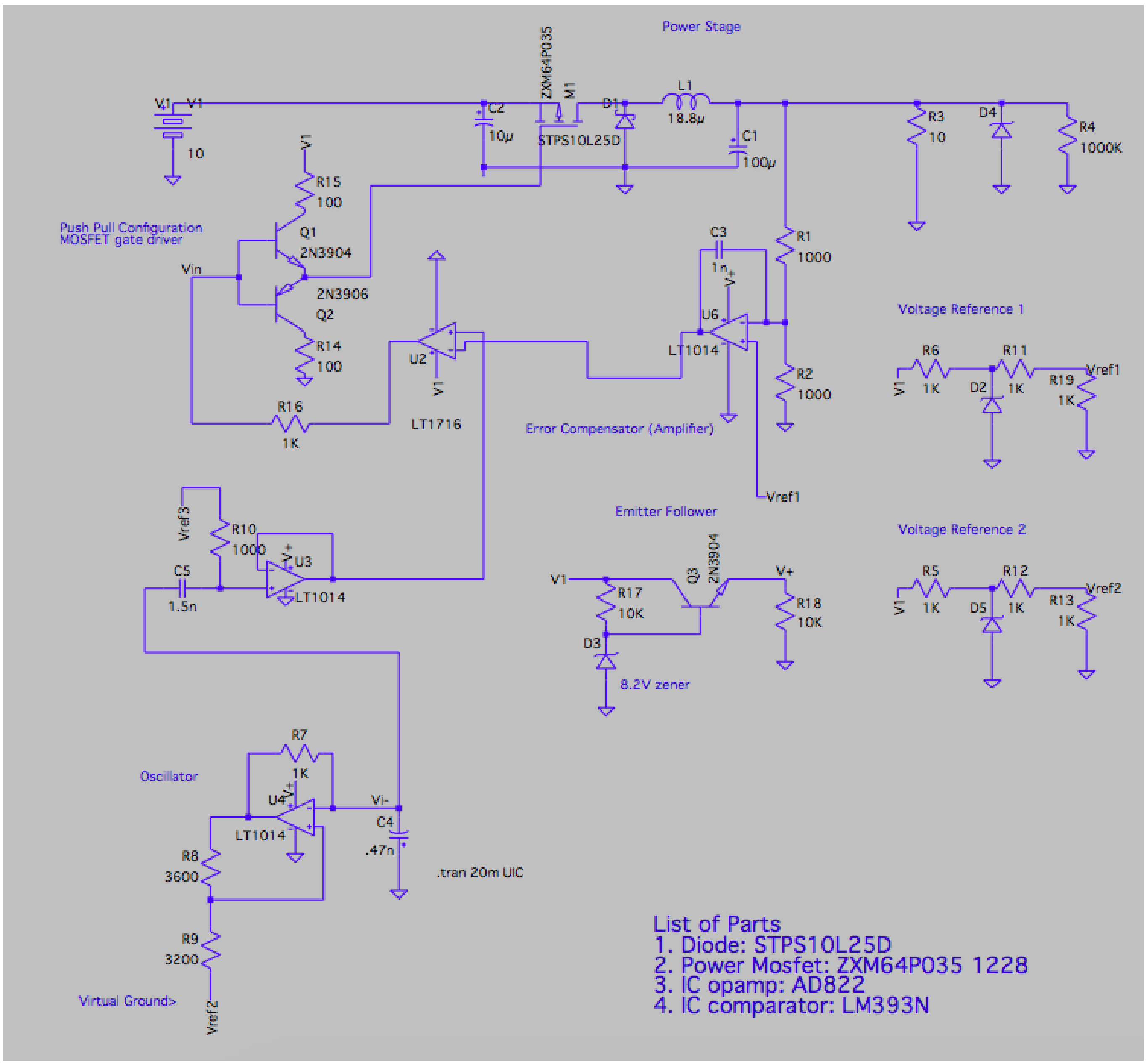


Fig 5. Complete buck converter circuit

Rails

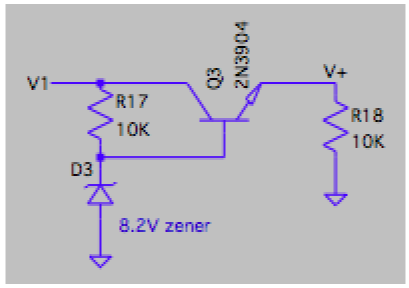


Fig 6. Emitter follower voltage source

The rails operate at 7.6 volts and are used to operate the opamps (AD822) in the control circuitry. An emitter follower bjt (2N3904) configuration is used as a voltage regulator. The collector and base are tied together with a 10K resistor and then the gate is tied to ground through an 8.2V zener diode. With a 10-15 volt input on the collector node the emitter node is 7.6 volts.

I used a bjt instead of a possibly more efficient voltage regulator ic because I was, in the spirit of design and learning, trying to limit the number of ICs I used. The emitter follower option was better than solely using a voltage divider or zener because it can source a higher current with more efficiency.

At the same time, if I were to redo this project the rails are one area I would definitely improve either by using an IC or increasing the complexity of the voltage regulator.

Buck

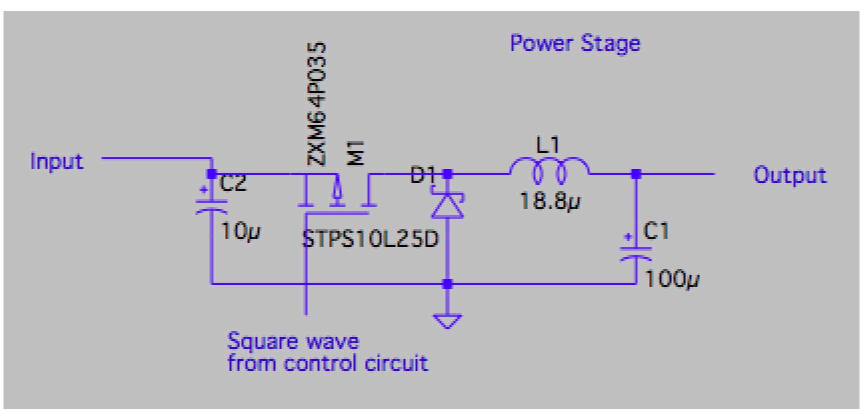


Fig. 7 Buck stage

The power stage uses a normal buck topology to buck the input 10-15 volts to a 5 volt output. The circuit includes a power mosfet, a schottky diode, an 18.8uH inductor and a 100uF capacitor. The power mosfet (ZXM64P035) was selected to have low gate drive, low threshold, and a relatively fast switching speed. It had to be fast enough to switch on the 100-200 kHz range and have a low enough threshold that it could be turned on or off with what the rails supplied. I tried to drive the mosfet's gate solely through a comparator because I hoped that gate drive would be low enough but ended up needing a push-pull amplifier as a current source because the gate capacitance was too high. The mosfet has an Ron of .075 ohms, a threshold voltage of -1.0V, and a drain-source breakdown voltage of -35V.

The low power drop schottky diode (STPS10L25D) was chosen to have small power dissipation in order to keep the converter as efficient as possible and to have a sufficiently high peak reverse current to avoid breakdown. The diode has a forward voltage of 0.07V at the 500mA operating point of the buck converter for a power dissipation of .035W. It also had a peak reverse voltage of 25V which was plenty high considering the max input voltage to the system was 15 volts.

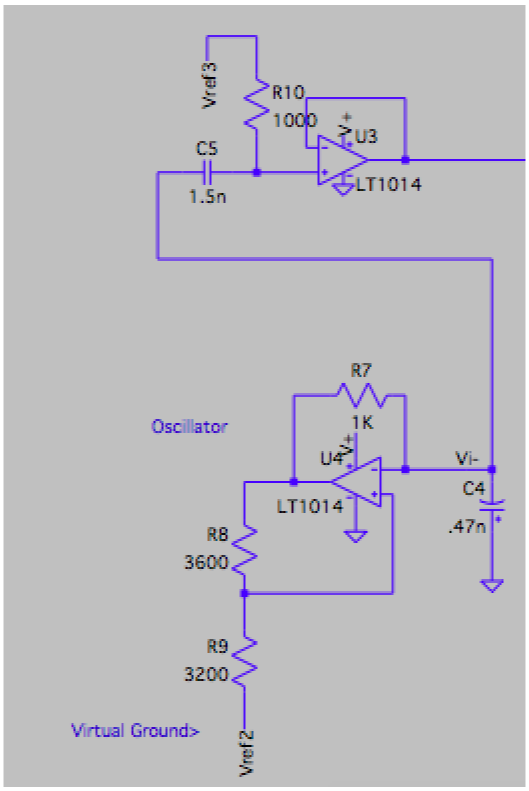
The inductor had a series resistance of 35 milliOhms which also contributed to power dissipation. The 18.8uH inductor value was chosen based on the maximum operating current, switching frequency, and output voltage.

The idea behind the buck converter is that the mosfet is turned on and off at a certain frequency acting as a switch. When the switch is closed the diode is reverse biased and the input charges up the inductor and capacitor. When the switch is open the input is disconnected and the diode is no longer reverse biased. The diode shorts to ground and the inductor and capacitor discharge, flowing through the diode. By varying the duty cycle, the amount of time the mosfet is on or off is changed affecting the amount the inductor and capacitor are charged and discharged and thus varying the output voltage. The decrease from input voltage to output voltage comes from the inductor. When the inductor charges, the current flowing through it increases. This produces a voltage drop, reducing the voltage at the output.

A buck converter can operate either in continuous or discontinuous mode. In continuous mode the inductor never fully charges or discharges leading to a simple transfer function where the output voltage is related to the duty cycle by $D = \frac{Vo}{Vi}$. Since a duty cycle can never be greater than 1 the output will always be less than the input. In discontinuous mode the transfer function is more complicated because current through the inductor is zero at certain times. I initially aimed to operate in the more straight forward continuous conduction mode when I was designing the circuit. However the inductor I chose was too small and the circuit, when built and tested, operated in discontinuous conduction mode instead. Interestingly, this didn't end up affecting the output voltage because the feedback control circuitry was able to keep the output at 5 volts.

One design consideration I faced was that increasing the capacitor on the output did not decrease the ripple on the output. This was because my capacitor was charging and discharging the same amount, producing the same ripple regardless of whether the output capacitor increased. To reduce the ripple I had to instead increase the switching frequency that the control pwm was operating at so that the output capacitor didn't charge and discharge as much. Also, by operating at a frequency above human hearing the output when used to power the audio amplifier produced a cleaner sound.

<u>Control</u>



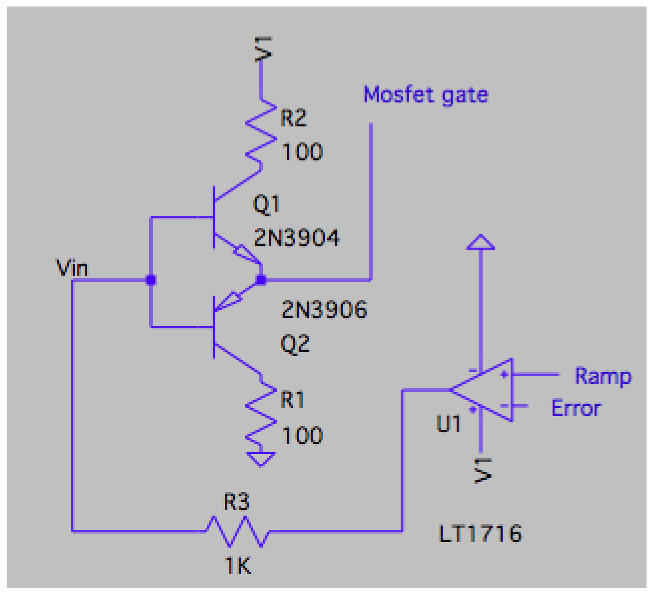


Fig. 8 *Left:* Ramp Oscillator *Right*: Comparator and Gate Driver

The control circuitry takes the output of the buck converter compares it with a reference voltage and then outputs a duty cycle to the gate of the power mosfet based on how close the actual output is to the desired output. There are four distinct parts to control circuitry: The error amplifier, oscillator, comparator, and mosfet gate driver.

First, the error amplifier is an opamp in a low pass filter configuration configuration where the positive input node is the voltage reference and the inverting input node is the buck power stage output. It essentially is integrating or doing a continuous summing of the error where there error is the difference between the power stage output and the reference voltage. The error amplifier outputs a number between the rails depending on how far off the power stage output is from the reference. The reference voltage was achieved with a zener diode and a voltage divider. Choosing an appropriate corner frequency was a challenge in this part of the design.

Next, the oscillator produces a ramp to be compared with the error amplifier's output. To produce a ramp an opamp in an oscillator layout produces a square wave which is run through an integrator to produce a triangle wave. In order to achieve an oscillation when the op amp is powered between ground and the rail a virtual ground was needed part of the circuit. This second reference voltage was again created using a zener diode and voltage divider configuration. The oscillator produces a wave at a frequency of 150kHz.

One design consideration that took some planning and deliberation was the coordination between the ramp and error amplifier output. It was crucial that the error output be on the same voltage scale as the ramp. This is because the comparator takes in the error signal and outputs high when the triangle wave is above the error and low when the triangle wave is below the error. Thus the max and min of the triangle wave had to be the same as the max and min of the error amplifier to fully utilize the complete range of possible duty cycles.

The comparator outputs a square wave of varying duty cycle based on how high the error is. As explained above, when the triangle wave is above the error the comparator goes high and when the triangle wave is below the error the comparator goes low. The output is then passed through a mosfet gate driver because the comparator alone doesn't output enough current to charge the gate sufficiently to turn the mosfet on. The amplifier used was a bjt push pull configuration. This was not the best option because the output is never completely high or completely low. In other words, the output never goes to either rail which means more power is dissipated than if another configuration is used.

One design challenge was achieving stability. The circuit at first only stayed on (ie output the same as input) or only stayed off (ie the output is zero). Getting each part of the control circuitry to work properly together was a challenge that a fair bit a time was spent working on.

The opamps used (AD822) were chosen for their versatility and low power consumption. While in the actual buck circuit the op amps operated solely on a supply of ground and 7.6V I wanted the freedom to be able to adapt the design to operate at a wider range of voltages. The opamps chosen fit this need operating with single-supply capabilities from 5V to 30V rail to rail. The AD822 also had a satisfactory slew rate of 3 V/us.

The comparator used was a LM393. It is a low-power, low-offset voltage dual comparator that was powered directly off of ground and the input to the buck converter. This fit my criteria for power consumption and operational rail voltages.

Output

The output of the buck converter when operating properly is 5V with ripple no greater than +/- 0.25 volts. To keep the power stage operating properly even when there is no load on the system a 10K resistor was put on the output. In addition, there was a zener 6.1V diode on the output to prevent voltage spikes that could possibly damage the electronics being charged.

With inputs down to 1.9V we were able to successfully charge an iphone and play music from an iphone using a class D amplifier built during a previous lab. This involved supplying 500mA of current at 5V. As a side note, the circuit continued to work even under short circuit conditions. The iphone charging cable we were using to test the project had a loose connection that shorted but it had no effect on our circuit. If there was more time we could have added short circuit protection in the form of a fuse.

Testing - Fiona

After designing a working spice model I built the circuit section by section on a breadboard. I had to consider the best way to lay out the components on the breadboard and properly allocate rails.

First the power stage was built and tested. Applying 10, 12, and 15 volts to the input I varied the duty cycle of a square wave from a signal generator to drive the mosfet. Using a scope probe on the output I was able to confirm that the output changed as predicted based on the duty cycle being used. Next I built the oscillator and confirmed that it produced the proper triangle wave after passing through an integrator. Once the oscillator was functioning I built the rest of the control circuitry. The error amplifier couldn't be easily tested to see if it was working as an individual unit so I tested the entire buck converter system together once the controls were built. I used the scope probe to debug the circuit and discover which components were not functioning properly. Finally I built and tested the voltage regulator and references for the rails so that the buck converter could operate off of a single input supply.

The complete buck system was tested by varying the input between 10 and 15 volts and ensuring the output stayed at 5 volts with an acceptable ripple of +/- 0.25 volts for a range of loads on the output. All testing occurred in a safe environment with safety goggles and a current limited voltage source.

Design Experience - Fiona

Designing a buck converter was a completely new experience for me. I had never built or even studied how switching converter worked and I had very limited experience with power electronics. I learned a lot by reading various journal articles, websites, and application notes from places like Linear Tech and Texas Instruments. These sources gave me insight into typical topologies of power converts and many of the challenges in building a buck converter. It was interesting to confront issues such as power consumption and efficiency and to try to improve by adjusting small details in the design. Even in choosing to use a boost buck converter design we read about other options such as using cuk and SEPIC converters instead. In a future project it would be interesting to build one of these other converter designs to compare operating performance.

Creating a working feedback control also gave me an understanding that studying in class from a book never would. Issues such as stability and poles which I have learned about in class suddenly became much more applicable when the output went high or went low because the system wasn't stable. Reading papers and websites online I gained an appreciation for how quickly control systems can get complicated.

Another aspect of this project which taught me a great deal was getting components with the right specs. Deciding which component to choose often involved trade offs in energy consumption or other features. This was a part of engineering I had never spent much time thinking about until I designed the buck converter.

There are many ways the buck converter could be improved and the project expanded. Building a more sophisticated controls circuit would be a really complex and informative project. Also, increasing the efficiency of the buck system is an issue that even designers at IC companies are working on improving.

System Testing - Alex and Fiona

The project was separated into two stages: the buck and the boost. These stages were each designed, built, and tested independently of each other before the two were combined to produce the final product as described above. While this approach might not have been the most efficient or elegant solution it allowed for a fair division of labour where neither of the people working on the project were fully dependent on the other.

The two stages were easily joined by connecting the output of the boost to the input of the buck. Various input voltages were then applied to the boost stage while the output of the buck stage was connected to various loads and monitored. A constant, steady 5 volt output was achieved with inputs ranging from 15 volts all the ways down to 1.4 volts. After ensuring the system worked using a voltage source we tested the circuit using two AA batteries in series and were able to produce a 5 volt output. We were then able to demonstrate the 5 volt output by charging an iphone and powering a class D audio amplifier which successfully played music without any audible problems.

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