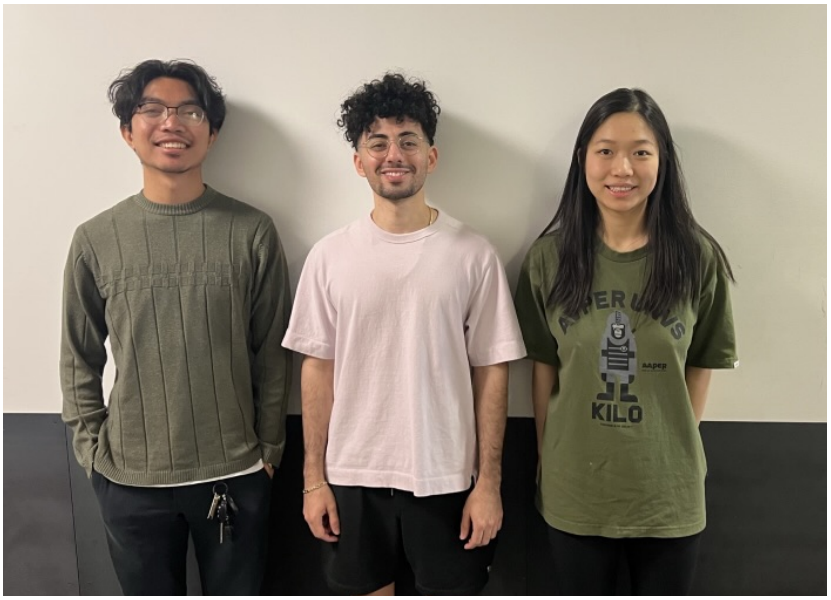
ECE 196 SP23

UC San Diego
JACOBS SCHOOL OF ENGINEERING
Electrical and Computer Engineering

Adjustable DC-DC Booster



Team Name	ABZ Security
Team Members	Jingyi Zhang, Kevin Burgos, Tomik akhverdyan
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Introduction

DC-DC Boosting is the operation of increasing the voltage in your circuit. Common batteries like the 18650 are 3.7v (for good reason), however some sections of circuits have goals that require more than 3.7v. Instead of adopting less common, higher voltage batteries or adding in a second higher voltage battery, we can simply step-up/boost the 3.7V. The benefit of this is a circuit that is able to achieve a large spectrum of voltage, thus being able to do more operations, all while keeping one common battery.

Learning Objectives

- Bullet list of concepts to be covered
- DC-DC Booster Equations/Mathematical Theory
- LM2577-ADJ IC basics and data
- LM2577-ADJ IC Usage

There are many ICs that allow fixed or adjustable voltage boosting. For this workshop, the IC we will be discussing is the LM2577-ADJ IC made by Texas Instruments.

Background Information

In our life, there are lots of occasions when a boost converter is needed. The boost converters are often used in power supplies for LEDs (i.e. Macbook LED backlit keyboard), Speakers, motors, battery packs for electric automobiles, and many other applications. Specifically, our project for the quarter is a door alarm which includes a louder buzzer that requires boosting voltage, thus a DC-DC boost converter is used.

Getting Started

For the building of a DC-DC Boost Converter, there are two options.

1. PCB-based
2. Solderboard-based
3. Breadboard-based

Required Downloads and Installations

If one wishes to make a PCB-based DC-DC Boost Converter, KiCad is required to design it. KiCad is compatible with Mac and Windows. This is optional.
LM2577 Datasheet:
https://www.ti.com/lit/ds/symlink/lm2577.pdf

Required Components

Component Name	Quantity
LM2577-ADJ	1
100uH Inductor	1
680uF Electrolytic Capacitor (25v+ rated)	1
0.1uF Capacitor	1
0.33uF Capacitor	1
17.4k Ohm Resistor	1
2.2k Ohm Resistor	1
18650 3.7v LiOn Battery	1
Adjustable Resistor (potentiometer) or 2k Ohm Resistor	1
Breadboard (if building breadboard-based)	1
Jumper wire (if building breadboard-based)	few
Solder board (if building solderboard-based)	1

Required Tools and Equipment

For Breadboard-based:

1. Jumper wires
2. Breadboard
3. Voltmeter

For Solderboard-based:

1. Soldering iron
2. Solder
3. Solder wick (flux)
4. 70-99% isopropyl alcohol
5. voltmeter

For PCB-based:

1. Soldering Station
2. Computer
3. Reflow Oven
4. Stencil
5. PCB Manufacturing
6. Voltmeter

Part 01: DC Boosting Equations and Basics

Introduction

In this section we will be teaching about the mathematical basics of DC to DC Voltage boosting, the derivation of DC-DC booster equations will be presented.

Objective

- List the learning objectives of this section

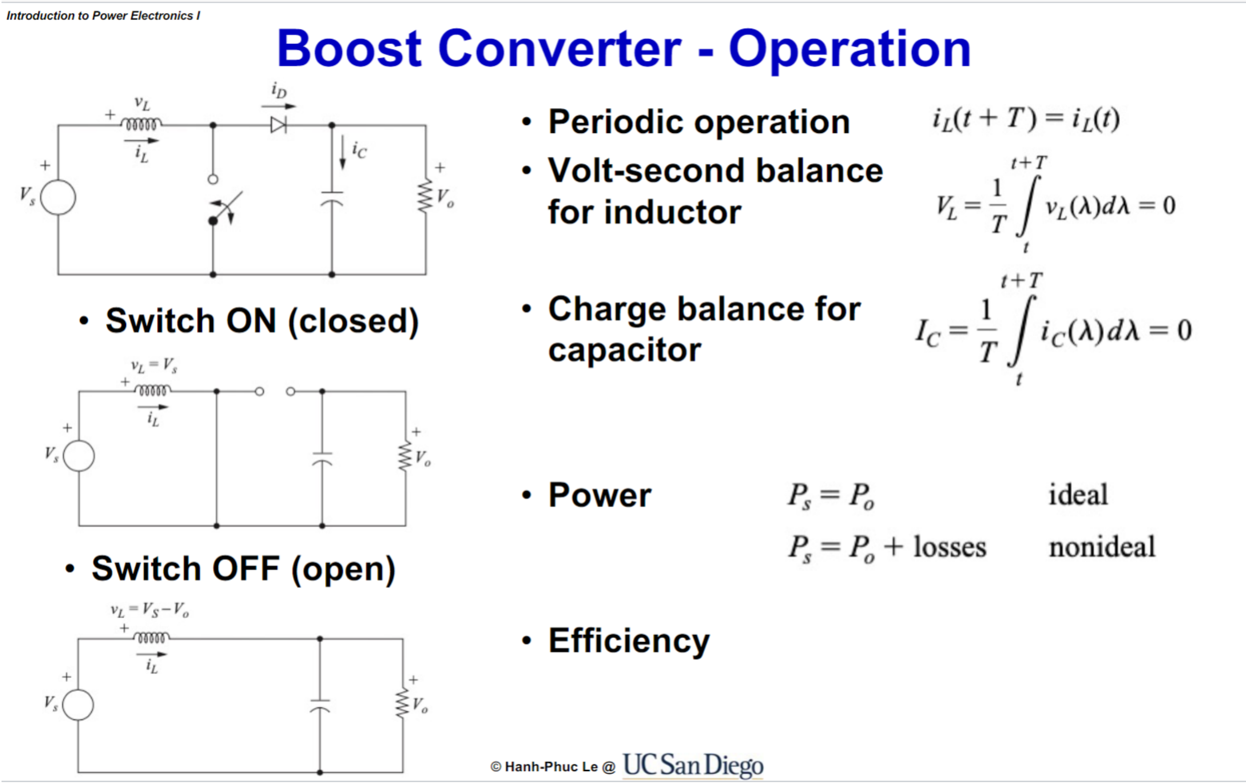
Background Information

- Basic knowledge in Buck/Booster circuits required
- Basic knowledge in circuit switches and duty cycle required

Components

- None

Instructional



A boost converter is operated in continuous conduction mode and assumed to be ideal for the following conditions. Inductor is charged during duty cycle DT (switch ON) and discharged during (1-D)T (switch OFF) A duty cycle or power cycle is the fraction of one period in which a signal or system is active. A period is the time it takes for a signal to complete an on-and-off cycle.

$$(\Delta i_L)_{\text{closed}} = \frac{V_s DT}{L}$$

Inductor current ripple while the switch is ON. (DT)

$$(\Delta i_L)_{\text{open}} = \frac{(V_s - V_o)(1-D)T}{L}$$

Inductor current ripple while the switch is OFF. (1-DT)

$$(\Delta i_L)_{\text{closed}} + (\Delta i_L)_{\text{open}} = 0$$

$$\frac{V_s DT}{L} + \frac{(V_s - V_o)(1 - D)T}{L} = 0$$

$$V_s(D + 1 - D) - V_o(1 - D) = 0$$

Steady-state operation: periodic

Since the sum of the current ripple while ON and OFF equals to zero, the expression of Vo in terms of Vs is displayed below:

$$V_o = \frac{V_s}{1 - D}$$

The Value of Vo depends on the value of Vs and the length of duty cycle.

Part 02: LM2577-ADJ Basics and Data

Introduction

In this section we will be learning about the ins and outs of the LM2577-ADJ component alone.

Objective

- Variations of the LM2577 family of ICs
- In Depth understanding of LM2577-ADJ adjustability
- Quick understanding of LM2577-ADJ internal features

Background Information

Give a brief explanation of the technical skills learned/needed in this challenge. There is no need to go into detail as a separation document should be prepared to explain more in depth about the technical skills

A well understanding of switching components is needed to continue. Here, we will be getting into deep details about the star of the show, our adjustable switching speed IC LM2577-ADJ. A basic understanding of reading plots like Voltage v. Current or Voltage v. Hz is needed as well.

Components

- **LM2577 Datasheet:** https://www.ti.com/lit/ds/symlink/lm2577.pdf

Instructional

As opposed to fixed booster converters, the LM2577-ADJ has a dedicated feedback line to vary switching speeds, thus varying output voltage. Let's build our way to getting an in-depth understanding on this IC by starting from the basics, the internal design.

For this workshop, we will be using the LM2577T-ADJ/NOPB (adjustable, THT, straight leads). For the sake of simplicity, we are referring to the LM2577T-ADJ/NOPB as "**LM2577-ADJ**". Any of the other ADJ (adjustable) variations will work as well.

See product coding below for more variations:

Product coding:
LM2577**X**-**Y/Z**

Where X is:

- 'T' for THH
- 'S' for SMD

Where Y is:

- 'ADJ' for adjustable boosting
- '12' for 12v boosting
- '15' for 15v boosting

Where Z is:

- 'NOPB' for straight leads
- 'LF03' for staggered leads

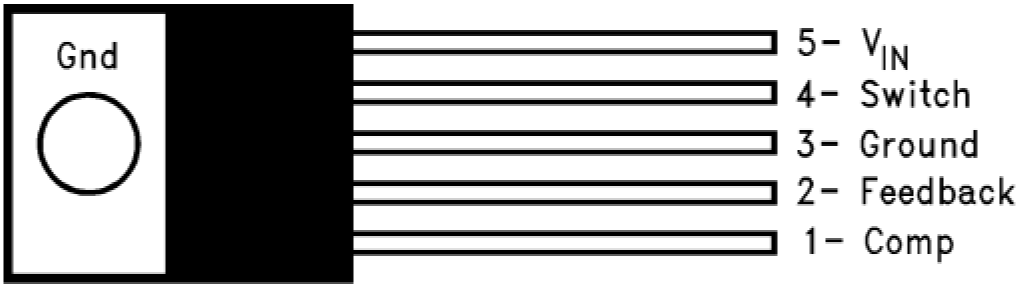


Figure: LM2577T-ADJ/NOPB Pin I/O Layout

As far as maximums go, the LM257-ADJ is very versatile IC. It is recommended to stay a fair amount below the Absolute Max Ratings. Please view the Absolute Max Ratings below and ensure to never go above it:

Absolute Max Ratings

Max Input Voltage	45V
Max Output Voltage	65V
Max Output Currently	6A
Max Temperature	260C

Secondly, view the Recommended Max Ratings and ensure this is the actual limit of which you operate this IC. Operating anywhere above the Recommended Max Ratings may result in unstable behaviors such as, but not limited to, excessive heat or ESD tripping.

Recommended Max Ratings

Max Input Voltage	40V
Max Output Voltage	60V
Max Output Currently	3A
Max Temperature	150C

Typical application of the LM2577-ADJ is fairly simple, and comprises only 8 passive components listed above in the **required components** section. Keep in mind that this is the most simple, bare basic setup. More advanced setups will consist of parallels of smoothing capacitors and the ability to modulate R1 and/or R2 through a physical dial.

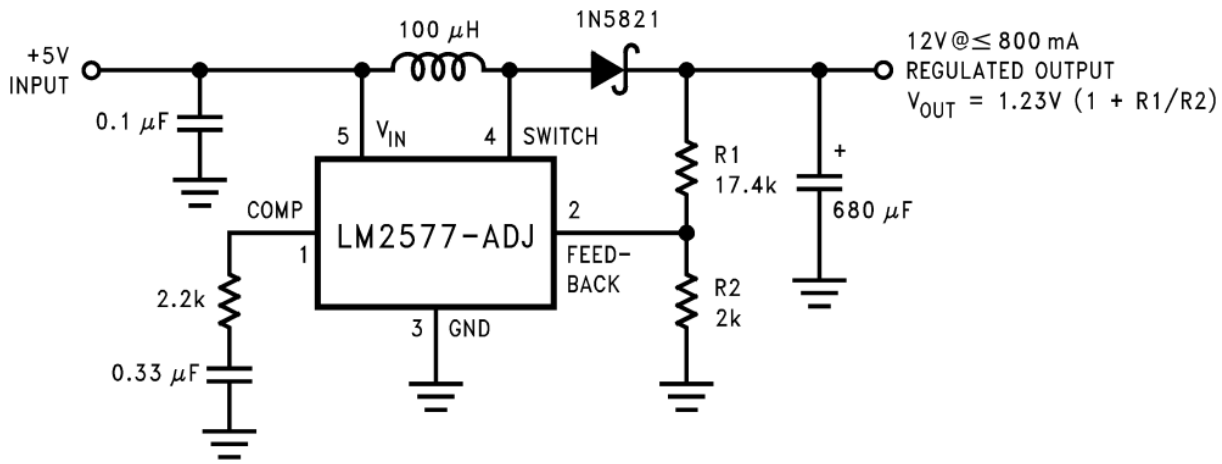


Figure: LM2577T-ADJ Boost Converting Typical Application

This basic setup does the job of boosting the 5v Vin to 12v Vout at a maximum of 800mA.

How exactly does the LM2577-ADJ achieve a higher output voltage?

The LM2577-ADJ switches the switch pin (4) on and off at a frequency of 52kHz. During the on phase, the 100uH inductor (L) creates energy through the switch pin (4). During the off phase, disconnecting the switch pin (4) allows the inductor to discharge energy through the 1N5281 diode (D) into the 680uF Electrolytic Capacitor (C3).

A feedback pin (2) measures the voltage between R1 and R2 to adjust the duty cycle of the switching. A higher duty cycle allows the switch pin (4) to stay in the “on phase” for longer, letting the 100uH inductor (L) create more energy to send though the 1N5281 diode (D), to the 680uF Electrolytic Capacitor (C3). This is the adjustability factor of the LM2577-ADJ.

How do we meet our desired output Voltage?

The LM2577-ADJ uses a fixed reference value of 1.23, and adjust it's duty cycle to meet the output voltage purely based off R1 and R2. To clarify, the output voltage will always follow the given output voltage formula:

$$V_{Out} = 1.23(1 + \frac{R_1}{R_2})$$

Formula: Output Voltage Formula

Due to this, the input voltage does not vary the output voltage, the output voltage will remain true to that formula as long as certain conditions are met. This is because input voltage is regulated down to 2.5v internally. As long the input voltage is above the regulation dropout voltage of 3.5v and below the target Vout, it is sufficient.

The diode is to ensure the energy from the discharging inductor (during the off phase) is driven into the capacitor. It is important that we must use a low forward voltage drop and high switching diode, such as a schottky diode.

The capacitor dictates maximum voltage. In our case, we are using an electrolytic capacitor that is rated for a maximum of 25v. Consequently, our system is only able to boost up to 25v. We also use a high capacitance component to ensure it's able to provide voltage solely from what it has stored till the next switch cycle where the inductor will charge it up again.

The inductor dictates the discharge rate and can affect maximum voltage. Changing our 100uH inductor for an inductor with a different inductance will cause the LM2577-ADJ to compensate by adjusting the duty cycle. This may affect the maximum voltage due to the LM2577-ADJ now having to adjust the duty cycle to achieve the same output voltage, bringing the IC close to the minimum or maximum duty cycle.

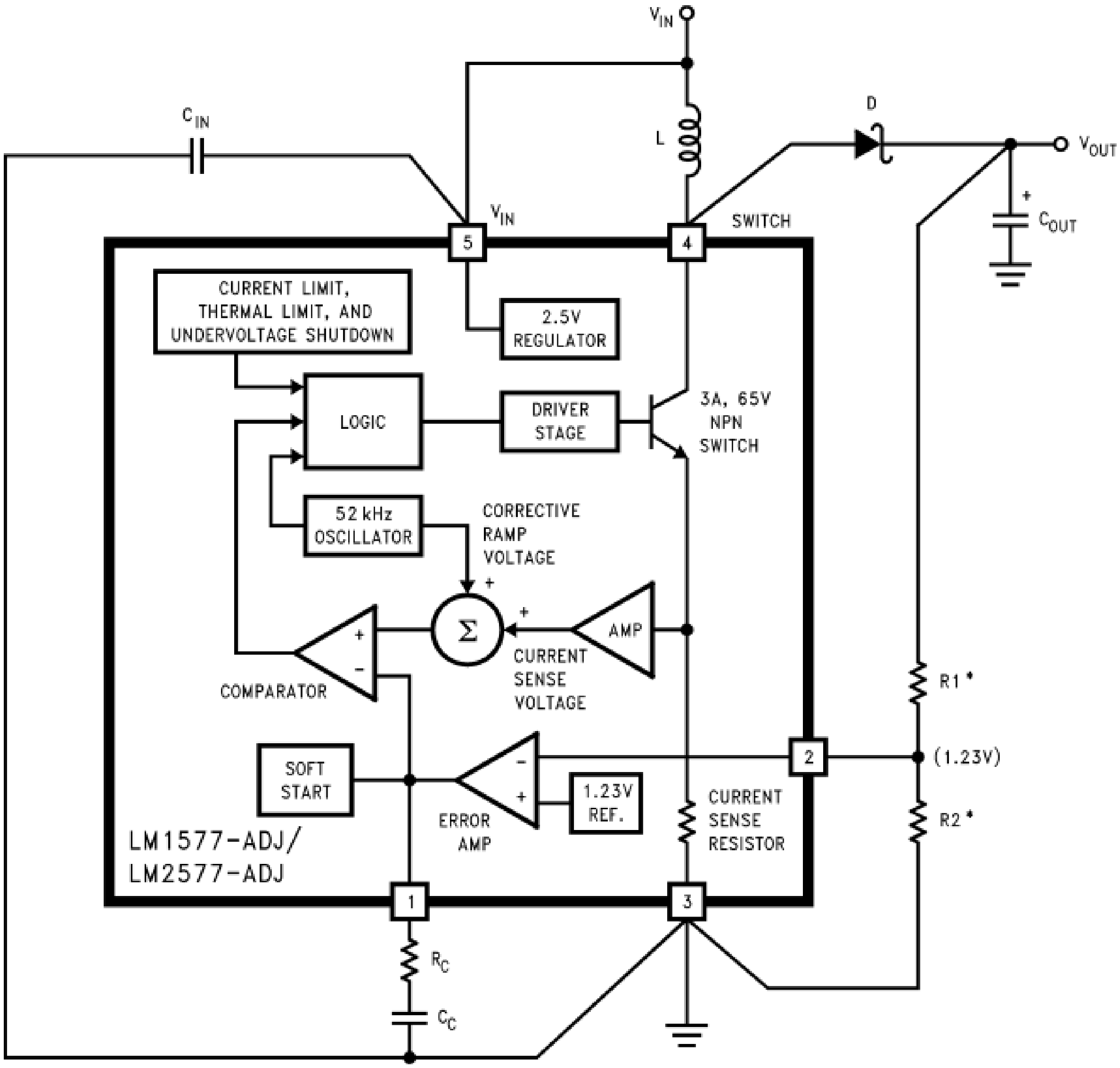


Figure: LM2577T-ADJ Internal Circuitry

Part 03: DC Boosting Circuit Setup & Real World

Introduction

In this final section, we will go over the setup of a DC boost converter circuit and some optional features. We will also go over some real world concerns.

Objective

- Setup a DC boosting circuit
- Educate yourself on the LM2577-ADJ and boost converters put into practice
- Optional additional features

Background Information

Depending on your goal setup (breadboard, solderboard, PCB), background knowledge in that type of setup is needed.

If setting up with a breadboard, knowledge in how breadboards work is required.

If setting up with a solderboard, knowledge in how solderboards work and experience with soldering is required.

If setting up with a PCB, knowledge in a software like KiCad, PCB manufacturing services, and PCB assembly/flowing is required.

Components

- Please see the required components in the “Getting Started” section.

Instructional

The setup of a LM2577-ADJ is fairly simple. There are however some important things to consider. Below is a KiCad schematic of a LM2577-ADJ seup. This specific setup boosts us from 3.8v to 12v.

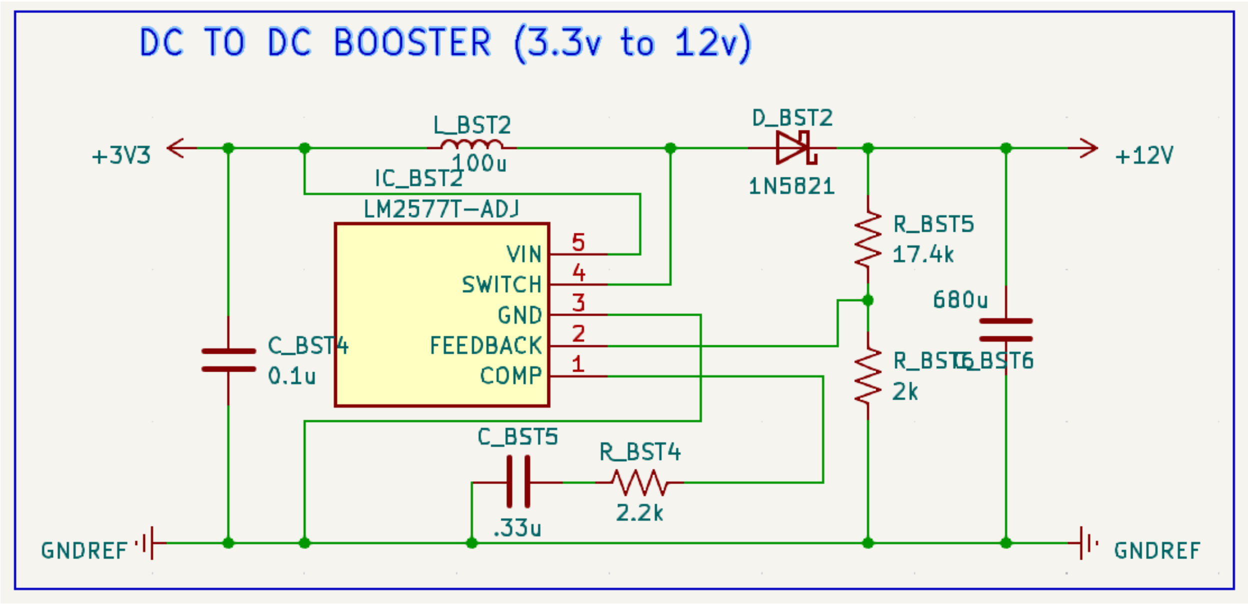


Figure: LM2577T-ADJ KiCad setup (3.3v to 12v)

This same setup can be done with breadboard, solderboards, or PCBs. The example section will cover substantially more about the in-practice setup. Below will consist of some very important aspects of real world practice.

Temperature

Boost converters have the potential to get very hot. Any IC getting too hot will lead to instability and issues with performance. **It's important to not touch the LM2577-ADJ while in operation.** Boosting from a very low voltage to a very high voltage will results in quicker switching, leading to higher temperatures. Although the LM2577-ADJ has a termal limit shut off safety system, this safety feature is a prevention of the IC destroying itself immediately, but will not do anything for long term damage.

Boosting to outrageous values like from 3.7v to 50v is not recommended. This will lead to over-the-top temperature, shortening the lifespan of the boost converter system and leading to very low output current.

Current Draw

When thinking of boosting voltage to something higher, it's natural to ask yourself what the drawback is. Current considerations are important. Normally, when boosting to a voltage 3-4x higher, we pay with a price of high input current and lower output current. We must have our input voltage be a high-current capable source.

For current draw, it is not too important to do the math on this, compared to voltage for example. An example of an **extremely poor design** is setting up the Vin as the digital pin output of a esp32 or an arduino. These output pins are not current-capable enough to power this system. An example of an **extremely great design** is having the Vin be voltage from a LiOn or LiPo battery. These power sources are very capable of providing enough current to power this. Note that using a battery to power a boost converter will drain battery life significantly.

This leads us to the issue of controlling when to provide power. A pin from an esp32 has the capability of being set high or low, allowing us to control the DC boosting with code. However, a direct connection to an battery does not, and will be consistently boosting with no on/off control. So how do we solve this problem?

Input Voltage Gating (optional)

To control when we start boosting with code, we will use a logic level mosfet that can be turned on and off with code. When turned on with code, current from battery will be let through to our DC booster system. When turned off, no current will be provided. For this, we can use a **RFP30N06LE** N Channel Mosfet.

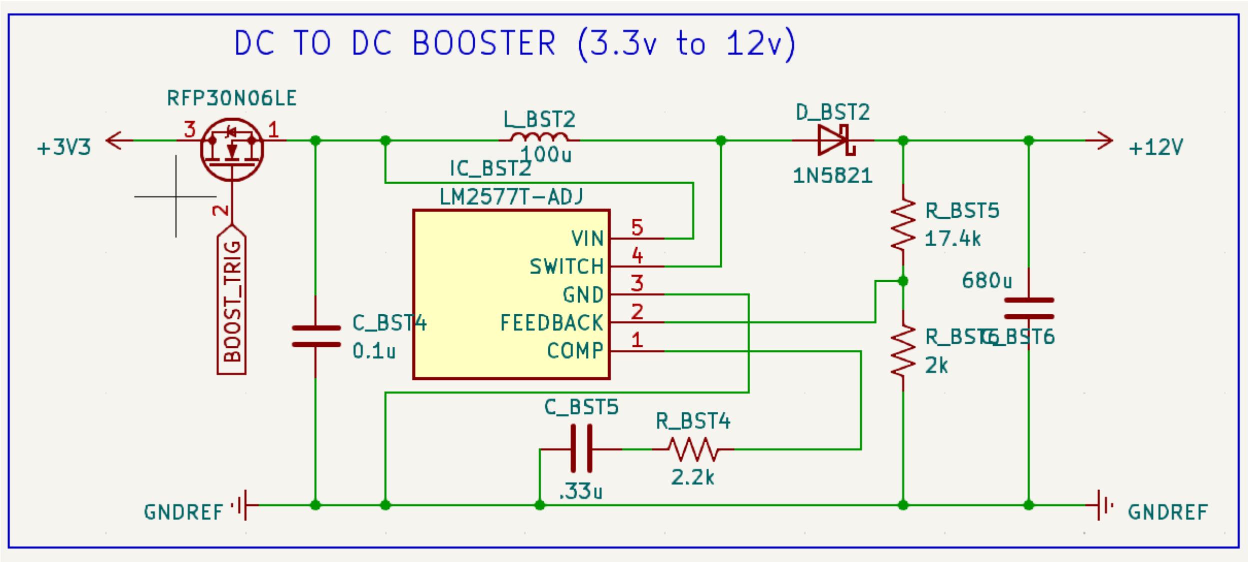


Figure: LM2577T-ADJ KiCad setup (3.3v to 12v) with RFP30N06LE Gating.

Setting a pin attached to the gate of the mosfet labeled "BOOST_TRIG" high will allow our system to work. Setting it low will turn our system off.

Note that our input voltage is shown as 3.3V, but can be an voltage that is compatible with the LM2577-ADJ. For a LiPo or LiOn battery, it would most likely be a 3.7V battery. Also, this mosfet is not imperitive to DC-boosting. It is simly an add-on feature if someone would like to DC-boost with code. Our system will work fine without one. For more information on mosfets, we recommend looking more into n-channel mosfets.

Adding adjustability parameter (optional)

As mentioned before, to adjust the value we boost to, we must change the resistance in R1 and/or R2. It is always an basic option to do the math on how much voltage your high-voltage component needs and simply use a fixed R1 and R2 for that amount only. We will see this design in our PCB-based example in the example section.

A secondary, more advanced option is to use a potentiometer in place of R1 or R2 (R1 is recommended for a more vast array of boost values) to be able to physically adjust the resistance, in turn adjusting how high we boost our voltage. This more advanced setup comes with a sense of danger.

When using a potentiometer, it's very important to measure resistance between the pins you will be using to ensure it is somewhere around the typical setup resistance when first installing. You must test your system with the values of the typical setup before making any adjustments to your potentiometer. This is to ensure that you do not accidentally boost extremely high, boost below threshold, or trip any LM2577-ADJ safety features due to a very low or very high potentiometer resistance value. From there, you may use a voltmeter between the Vout pins and **slowly** make adjustments to your potentiometer, ensuring you're stating between safe parameters. **If you hear a high pitch buzzing sound, shut off the system immediately.** We will see this design in breadboard-based and solderboard-based example in the example section.

Is using a boost converter right for you?

Using a boost converter overall is not a very efficient thing to do. A lot of current is lost to ground and to heat during switch cycling. The most energy efficient method would be to use another power source to separately power a high voltage component. However, in that case, space may be an issue and this may complicate your circuit more.

We recommend using the LM2577-ADJ to boost voltage in these scenarios:

1. You will be boosting to a reasonable level (2-3x Vin voltage)
2. Booster is plugged into a wired power source, like a USB
3. You do not care about battery life or will charge often
4. Mosfet is installed and will only activate in emergency situations
5. You have an extremely large battery
6. High voltage component requires little current

Resistors, Trace width, ground connection, inductor spacing, etc.

Any high voltage system, like potentially our LM2577-ADJ boost converter (depending on boost values), need to use components meant for high voltage application to prevent bottlenecking, high impedance, or burning out. We have already specified capacitor, inductor, and diode types. However, we must still specify minimums for resistor, trace width (if using PCB-based), via diameter (if using PCB-based), ground connections, inductor spacing, etc.

For resistors and capacitors, we would recommend using a higher wattage design. For throughhole resistors, we recommend a ½ watt size. For SMD resistors, we recommend a ½ watt 2010 footprint. We also recommend the 2010 size for capacitors as well. A smaller 1206 footprint for both would also work if you are boosting to something lower or require less current.

For trace width (PCB-based only), we recommend an absolute minimum of 20 mil (0.51 mm) for the entire system. If you will be boosting extremely high, we recommend 30 mil (0.75 mm). If you're intent design is breadboard or solderboard, all jumper pins are wide enough to support boosting.

For via width (PCB-based only), any jumping across layers should be a minimum of 30 mil outer diameter and 15 mil inner diameter. If will be boosting very high, we recommend 40 mil outer diameter and 20 mil inner diameter.

For ground connection (PCB-based only), we recommend have a more than solid connection between the battery and the output ground. We recommend multiple vias and a solid copper ground pour layer. A ground pour will also help with preventing inductor cross-talk.

For the inductor, we have a fairly strong magnetic field being generated during the charging/discharging process. Due to this, surrounding traces, capacitors, RF sensitive components, and data lines could be negatively impacted by this. We recommend a no-build zone in the surround areas, especially below the inductor. Since the boost converter is not a sensitive area, it's okay to build thes components closer to the inductor. However, we strongly recommend keeping any RF, data lines, or sensitive systems in general away from the inductor. For example, the ESP32 antenna or D+/D- data connections.

Examples

Introduction

In this section, we will show examples of a LM2577-ADJ based booster converter put into practice looks like.

Example

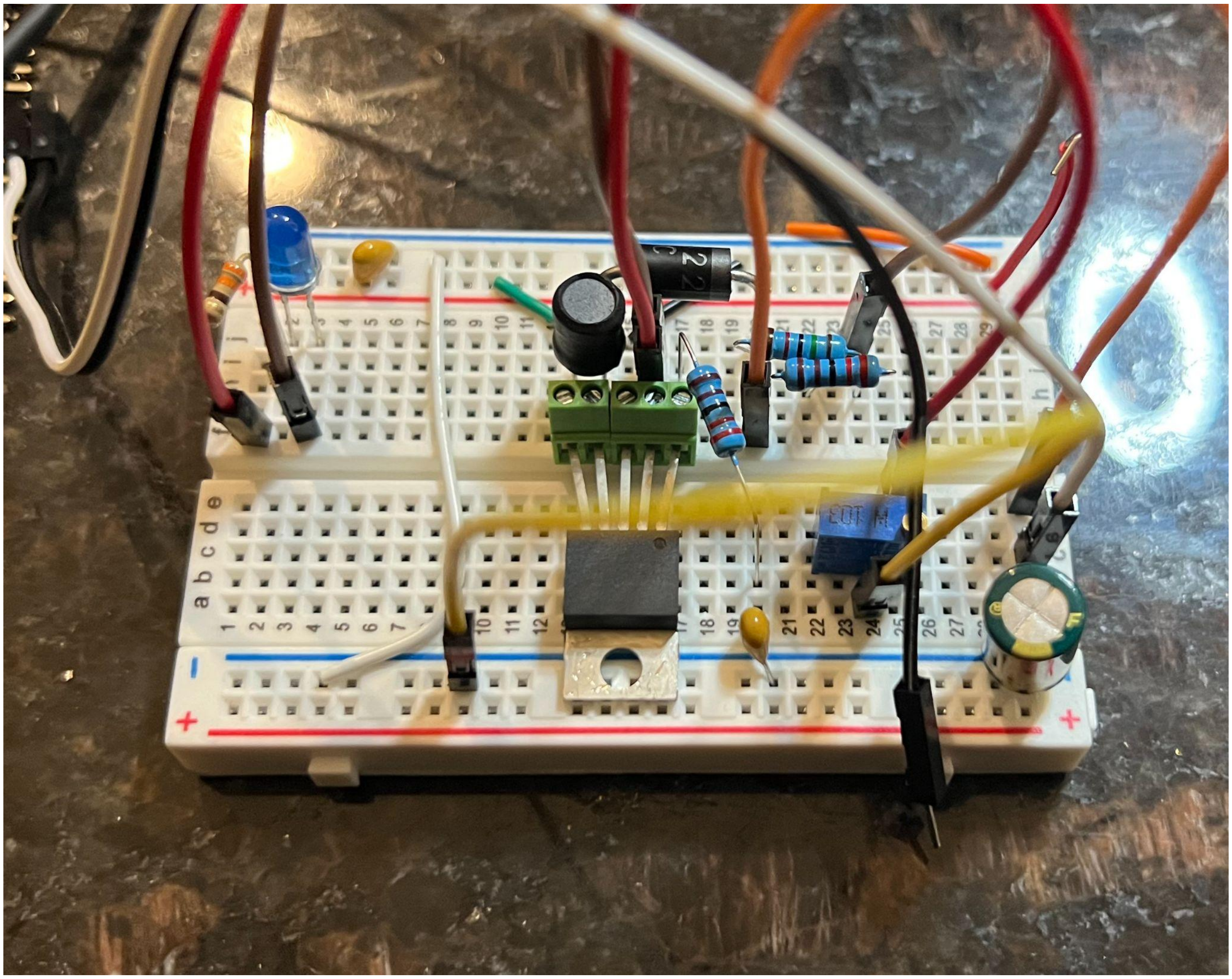


Figure: breadboard-based LM2577-ADJ booster converter with adjustable potentiometer

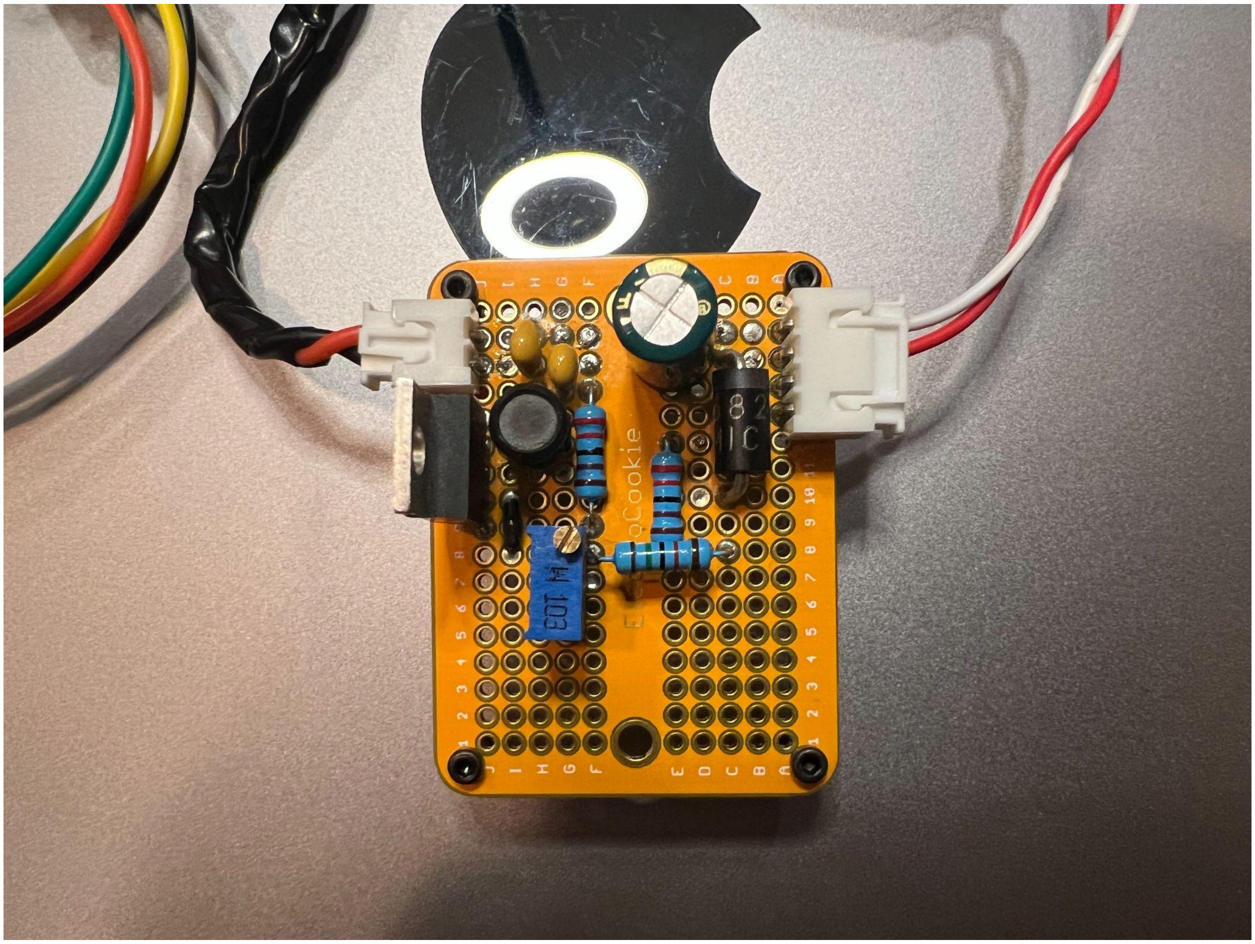


Figure: Solderboard-based LM2577-ADJ booster converter with adjustable potentiometer

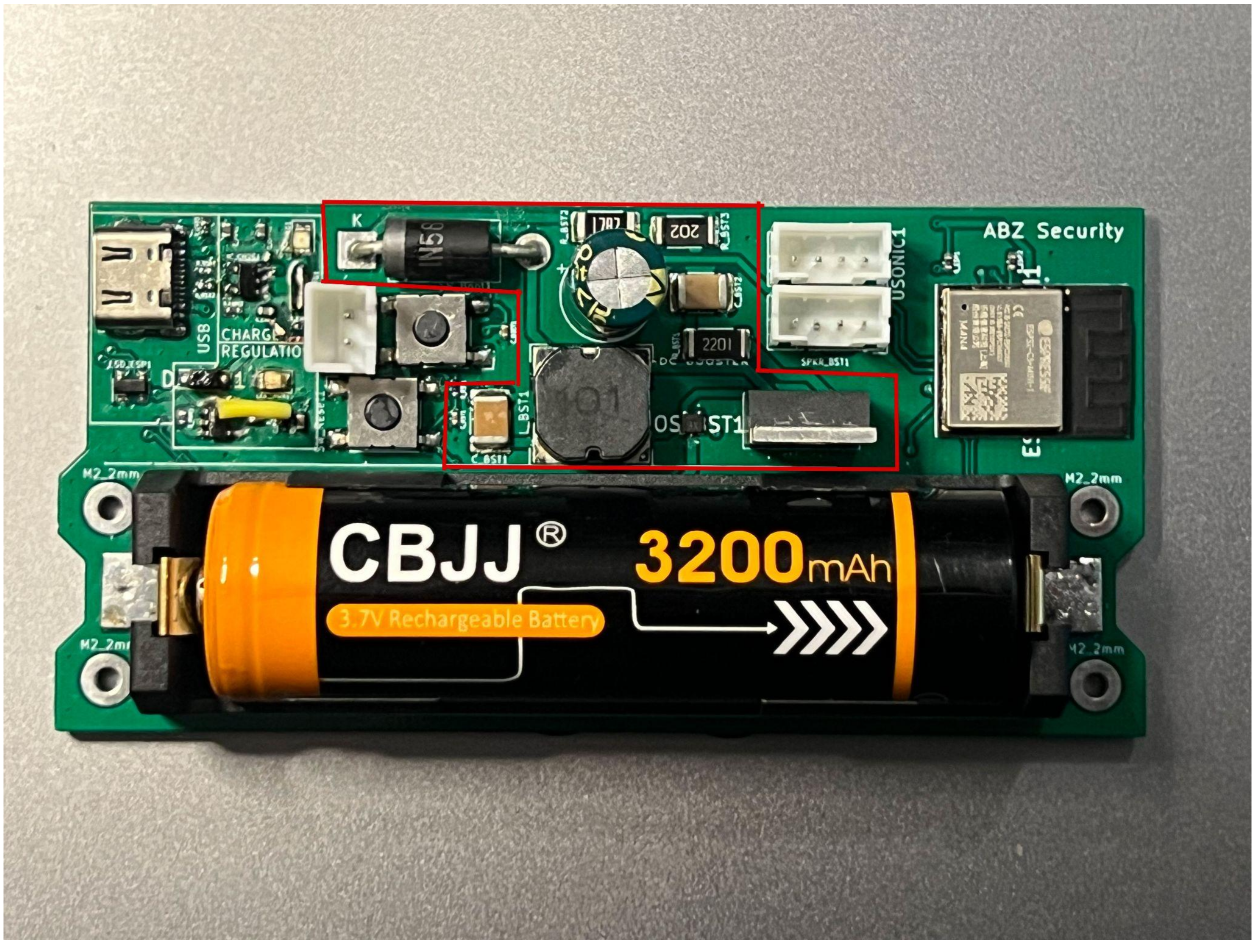


Figure: PCB-based LM2577-ADJ booster converter with fixed resistor for 3.7v-12v. (Shown in red)

Analysis

These examples are real world usage examples of three different ways someone can setup a LM2577-ADJ based boost converter to increase voltage. It's important to note that there are magnitudes of difficultly in your chosed method, and the most difficult one (PCB based) will yield the most compact and reliable design. Consequently, the easiest (breadboard based) will yield the least compact and least reliable design.

Additional Resources

Useful links

https://www.ti.com/lit/ds/symlink/lm2577.pdf

https://www.mouser.com/datasheet/2/308/rfp30n06le-1195941.pdf

https://learnabout-electronics.org/PSU/psu32.php