Physics Lab VP
Department of Physics
ETH Zürich

Anleitung Nr. ...

Constant Voltage Source

Rev. Hugo Doeleman
October 19, 2021

Contents

Abstract

In this experiment a constant voltage source is built around a transformer. The development of the power supply starts with a basic one, a diode with a capacitor, and is then gradually improved. The stages along the way are characterised and compared.

Chapter 1

Introduction

1.1 Constant Voltage Source

Many electronic applications require a source of a constant voltage (DC, *direct current*) in the range of few to 20 volts. Yet, the outcome of the famous War of Currents is that the power outlets deliver a sinusoidal alternating current – AC. In Switzerland, as in the rest of Europe, the voltage is 230V RMS (Root–Mean–Square, the effective voltage). The change of the 230V AC voltage into a several–volt DC one is the purpose of omnipresent power supplies. You may be even carrying one or two in your bag, for your cell phone, laptop, tablet or what-not. In this exercise you will learn how to build and characterise a constant voltage power supply.

In *constant voltage power supply* the word *constant* has a double meaning. The source should be independent on variations of the input voltage — it should be constant over time. The delivered voltage should also be independent on the load (delivered current). Throughout the exercise you will build different voltage sources and characterise how good are they in these two respects. The peak-to-peak fluctuations in time are called the *ripple*; the smaller it is, the better. The ripple is usually a function of load. The dependency of the voltage on the load is quantified by the *output resistance*, which is the slope of the U-I characteristics (output voltage as the function of the output current). The smaller the output resistance the better.

1.2 Components

1.2.1 Transformer

The transformer, photo in Fig. 1.1, transforms the 230V AC mains voltage down to nominally 15V AC, accessible on the yellow terminals. The box has a switch in front which lights up when on. It is good to always turn it off when modifying the circuit to avoid an accidental short–circuit. Exceeding the rated power of the transformer (printed on its package), for example in an event of a shorting its terminals, would destroy the transformer

Figure 1.1: The 260V/15V transformer used in the experiment.

if not for a fuse on the 230V AC input (below the plug).

1.2.2 Potentiometer

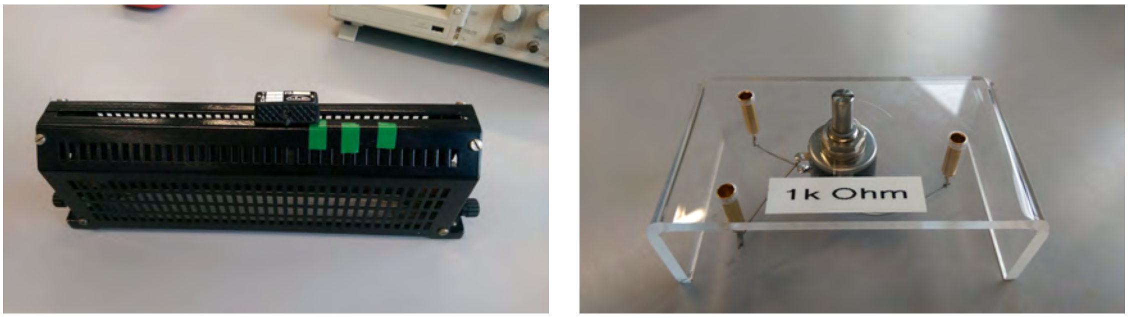

Figure 1.2: Two kinds of potentiometer. Left: high-power sliding type. Right: low-power rotating type.

A potentiometer is a long resistive wire with a movable brush that moves along it. Two terminals are connected to the ends of the wire. Resistance between those is constant and indicated on a potentiometer. The third terminal is connected to the brush. A potentiometer may be used as an adjustable resistance (between one of the wire end terminals and the brush) or as an adjustable voltage divider (the potential on the brush terminal is adjustable between the potentials on the other two terminals).

In this experiment there are two types of potentiometers, both shown in Fig. 1.2. One is a big, high-power sliding type. The other is a small, rotating type. When using a potentiometer to adjust the load, **always** use the high-power type, as you will have potentially high-currents there. The small types can only dissipate up to ∼0.5W of power before damaging.

Remember that you can combine potentiometers in parallel or in series to increase the adjustment range.

1.2.3 Capacitor

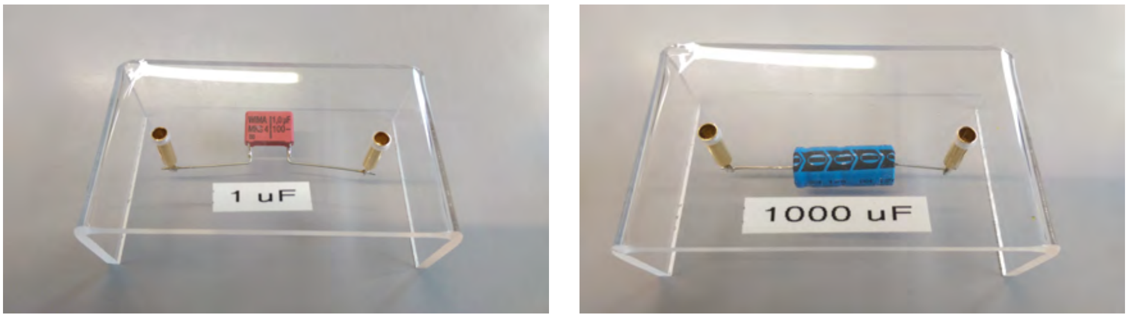

Figure 1.3: Two kinds of capacitors. Left: non-polarised ceramic; Right: polarised electrolyte.

Capacitors store charges and can be used, among others, to smooth voltage variations. The voltage U is proportional to the total charge Q stored, such that

$$C = \frac{Q}{U} \tag{1.1}$$

where C is the capacitance, measured in Farad, F. More often one uses smaller units: μF and nF.

There are two main types of capacitors. To a *non-polarised* capacitor voltage can be applied in either polarity. However, these are available only with small capacities, up to about a microfarad. Higher capacities are available with electrolyte capacitors (often called elkos in German), which are *polarised*. There is a big black arrow pointing at the negative pole printed on them. If a voltage is applied to this type of a capacitor in the wrong direction it will blow up. The peak voltage, in the right direction, should not exceed the rated voltage printed on the body to avoid breakdown.

For increasing frequencies different capacitors show different behaviour. Therefore one can often find different types of capacitors in parallel to improve the high frequency response while still having a high capacitance for low frequencies. Film- and ceramic capacitors are often used for high frequency applications.

Remember that you can combine capacitors to get effective capacities other then the nominal ones of the available parts.

Figure 1.4: A standard diode.

1.2.4 Diode

The basic function of a diode is to block a current flow in one direction. Diodes are used, among others, for *rectification*, that is AC-DC conversion.

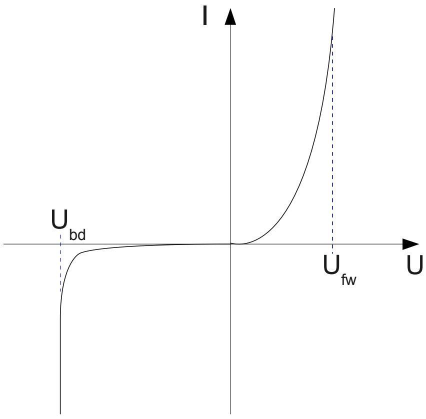

Figure 1.5: Current-Voltage characteristic of a diode.

More insight into a diode gives its current–voltage characteristic, shown in Fig. 1.5. When voltage is applied in the *forward* direction one quickly reaches a zero–resistance regime (vertical I-U curve). The voltage drop on a diode in this regime is about 0.6V, called the *forward voltage drop*. When voltage is applied in the *reverse* direction the diode is in an infinite resistance regime (horizontal U-I curve), blocking the current flow. When reverse voltage exceeds the *breakdown voltage* a standard diode breaks permanently.

In this experiment 1N4007 diodes are used (Fig. 1.4). Additionally B80R (Fig. 1.7) — a package of four diodes arranged in a full–wave rectifier (Fig. 1.6) is available.

1.2.5 Zener diode

A Zener diode has a voltage–current characteristic as a standard diode, but is designed to be operated at the breakdown voltage. When current flows in the reverse direction

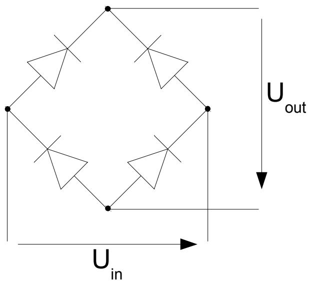

Figure 1.6: Schematic of a full–wave rectifier.

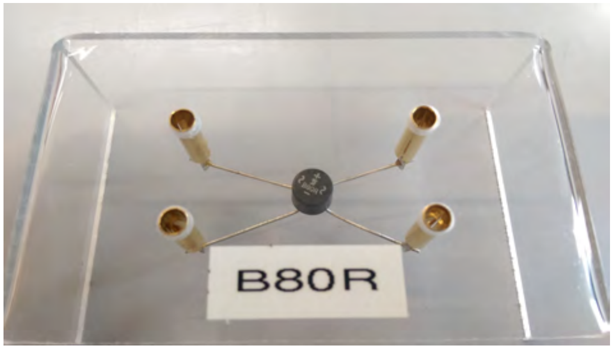

Figure 1.7: Four diodes making up a full–wave rectifier in one package

through a Zener diode, the voltage drop on it is constant in a wide range of currents. The breakdown voltage is given in the datasheet and is usually included in the part number.

The voltage drop on a Zener diode is often used as a constant voltage reference, as shown in Fig. 1.9. To get a good reference the diode has to be properly *biased* — a current has to flow in the reverse direction. Because in the breakdown regime diode has zero resistance the current has to be limited by other means, usually with a resistor in series. The value for R_Z depends on the rated current I_Z for the diode and the supply voltage U_0 to $R_Z = (U_0 - U_Z)/I_Z$. In the datasheet two current values are given: *test current*, which the manufacturer has used when characterising the diode, and *admissible Zener current*, exceeding which permanently breaks the diode. Take care not to do it. You can check if a diode is broken with a multimeter in the *diode mode*. When a diode is connected in the conducting direction the multimeter will measure the forward voltage drop, which should be around 0.6V.

1.2.6 Transistor

A (bipolar) transistor is a semiconductor device which uses a stack of three different semiconductor regions, either npn- or pnp-doped. The symbols and a sketch of the doping regions for both transistor types are shown in Fig. 1.11. For improved performance, the regions have a different doping concentration. In principle, the pins for emitter and collec-

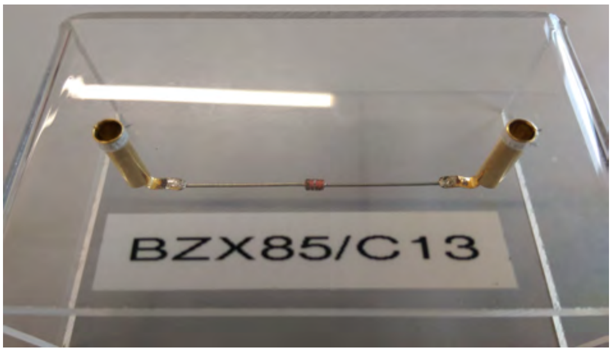

Figure 1.8: A Zener diode. The breakdown voltage is indicated as the last two digits of the part number.

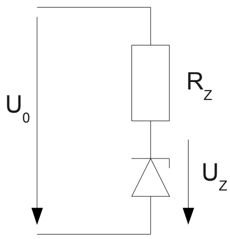

Figure 1.9: Reference Voltage U_Z generated by a Zener diode with serial resistor R_Z

tor can be switched. However, as the device is highly optimized, most of the characteristic properties of the transistor would degrade.

Here we describe the operation for an npn-doped transistor. For a pnp-doped transistor, the roles of collector and emitter are reversed. In normal forward-active operation the base-emitter (B-E) pn junction is forward-biased, whereas the base-collector (B-C) diode is reverse-biased. The current I_B flowing into the base gets amplified and a much higher emitter current I_E is generated. The increased current flows from the collector into the emitter such that the charge conservation $I_\mathrm{E} = I_\mathrm{B}+I_\mathrm{C}$ holds. The ratio $\beta = I_\mathrm{C}/I_\mathrm{B}$ is called *common-emitter current gain* and achieves values as high as 100 to 1000. The detailed physical process inside the transistor is treated in textbooks about semiconductor physics like [3, 4]. The current gain can also be used to amplify a voltage. Different circuits, both discrete and integrated, are developed in great detail in [5]. For most applications the forward voltage U_BE of the base-emitter diode can be assumed to be approximately $U_\mathrm{BE} \approx 0.6$ V.

The famous Art of Electronics [2] proposal to intuitively grasp the operation of a transistor are the following four rules (assuming an npn transistor):

1. **Polarity** The collector must be more positive then the emitter.

2. **Junctions** The base-emitter and base-collector circuits behave like diodes (see figure) in which a small current applied to the base controls a much larger current

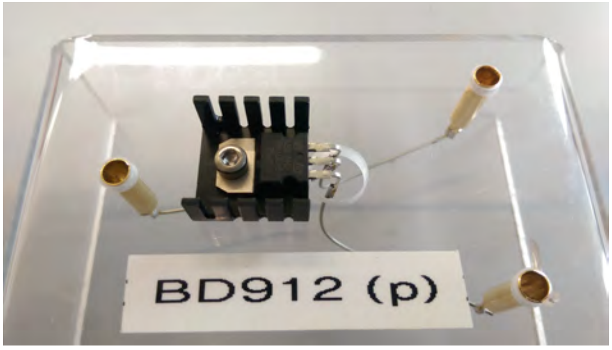

Figure 1.10: A pnp transistor. The legs are described in the datasheet.

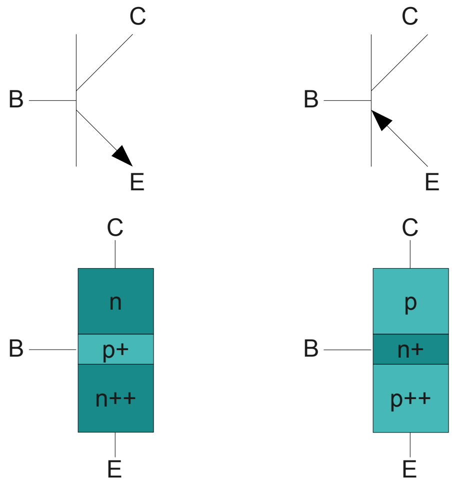

Figure 1.11: Symbol and doping profile of npn and pnp transistor.

flowing between the collector and the emitter. Normal the base-emitter diode is conducting, whereas the base-collector diode is reverse-biased, i.e., the applied voltage is in the opposite direction to easy current flow.

3. **Maximum ratings** Any given transistor has maximum values of I_C, I_B and V_{CE} that cannot be exceeded without costing the exceeder the price of a new transistor. There are also other limits, such as power dissipation ($I_C V_{CE}$), temperature, and V_{BE}, that you must keep in mind.

4. **Current amplifier** When rules 1-3 are obeyed, I_C is roughly proportional to I_B and can be written as $I_C = h_{FE} I_B$

Additionally, an crude intuitive picture of the transistor man is proposed, Fig. 1.13.

In the course of the experiment several side tasks are proposed whose role is to help understand the transistor's action in circuits.

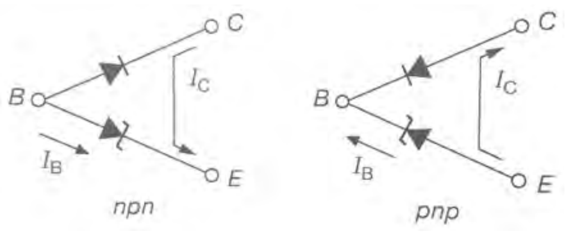

Figure 1.12: An ohmmeter's view of a transistor's terminals. Adapted from [2].

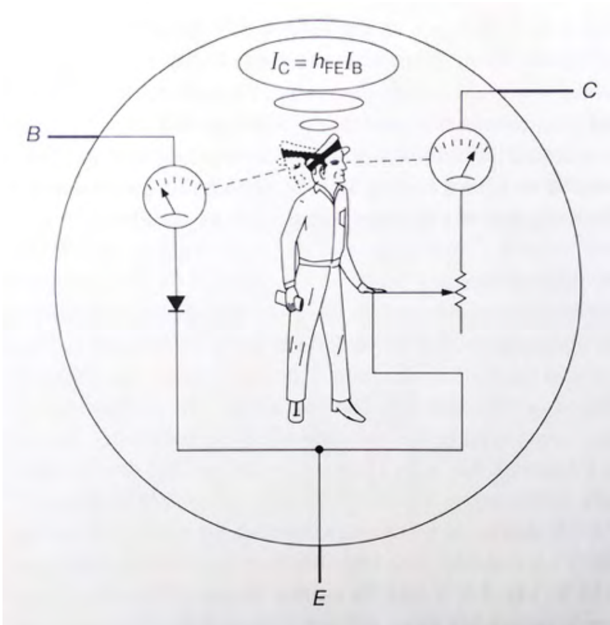

Figure 1.13: The transistor man. Adapted from [2].

1.2.7 Multimeter

You can do a variety of measurements with a multimeter. Most importantly voltage, current and resistance. The type of measurement is chosen with a large dial.

Multimeters have typically four terminals. The negative cable goes always into COM. Where to plug the positive cable depends on the type of measurement. For most of them it goes into the rightmost terminal. The exception is measuring a current (which, internally, is actually measuring a voltage drop over a build-in shunt resistor). Note, that there are two terminals for measuring current with different ranges. One measures currents up to 500mA, the other up to 10A. Both are secured with appropriate fuses. Mind, that if the device does not measure the current properly, the fuse may be blown.

The multimeter can measure both voltage and current in two modes: DC, where it shows the time average and AC, where it shows the RMS value. RMS stands for Root

Figure 1.14: A UNI-T multimeter used in the exercise.

Mean Square: the square root of the average square of the values.

The multimeter turns off automatically after some time to save battery, beeping just before it does. Any action, e.g. pressing the yellow *hold* button twice, prevents the shutdown.

1.2.8 Oscilloscope

An oscilloscope is a device to measure a voltage as a function of time. Typically they resolve from milivolts to tens of volts on timescales from seconds down to nanoseconds.

The voltage is measured between ground (the shell of the BNC connector, the black terminal on the cables) and one of the two inputs (the red cable terminals). Note in particular, that if you use two channels simultaneously, the black terminals are connected together through the ground. Do not let a current flow through that path.

The vertical axis, voltage, can be adjusted separately for both channels. You can set the scale (volts/div – volts per screen division unit) and the vertical position. Zero level for each channel is indicated with an arrow. For the horizontal axis, time, you can similarly change the scale (secs/div – seconds per screen division unit) and the position of the trigger point, indicated with an arrow on top. The trigger point is the zero time and is defined in the trigger menu. Typical definition is similar to ,,When voltage on CH1 reaches 0V on the rising flank.” You can adjust the voltage level to be reached for the trigged to fire with the trigger level knob. Normally the oscilloscope only refreshes the display when a trigger occurs. When viewing noisy signals it is useful to set the high–frequency noise rejection. You can use the autoset button as a starting point for adjustments.

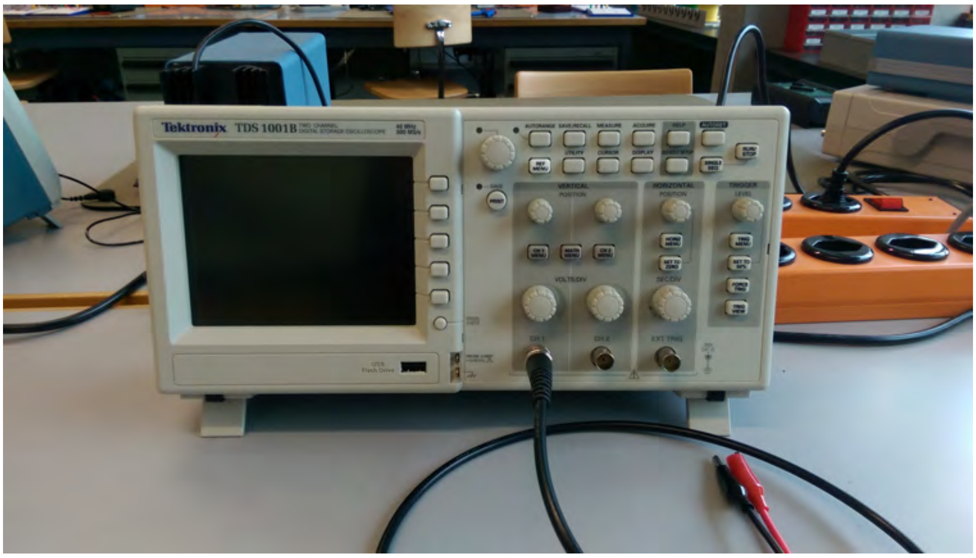

Figure 1.15: An oscilloscope.

The channel menu is accessed by pressing the channel button. Most importantly you can change there the coupling. DC coupling measures the voltage directly. AC couples the signal through a capacitor, which rejects the constant part. It is very useful when one is interested in fluctuations of the signal around some central value. If these fluctuations are very small and the central value is large, a DC coupled measurement will not show the fluctuations accurately. This is because the oscilloscope converts the incoming analog signals to digital values with a certain resolution. For example, if it is an 8-bit oscilloscope, it will divide the full range of the channel (set by the scale) into $2^8 = 256$ values, in which it bins the data. This limits the smallest differences you can resolve. So to measure small ripples on a large offset, switch to AC coupling and decrease the scale untill you see the ripples clearly.

The oscilloscope can automatically do simple measurements on the signals, like their frequency, Pk-Pk (peak-to-peak) or RMS amplitudes. It is important to know that adjusting the horizontal and vertical scales does not only change the display, but the actual connection to the digitiser. That means that in order to get an accurate measurement you still have to adjust the scales so that the signal is nicely visible.

You can store what the oscilloscope measures as CSV files or screen–shots (the former is preferred) on a USB stick for presenting it later in your report.

1.3 Further remarks

A few general remarks about these experiments:

- Whenever the assignment is to 'characterize' a voltage source that was built, this implies a measurement of the output voltage as well as the ripple voltage, both as function of the load.

- By 'load' we always mean the current that is flowing between the output terminals of your constant voltage source, which is not necessarily equal to the current coming out of the transformer, for example.
- For each measurement, you are expected to think for yourself what constitutes a useful range of values to measure.
- Make sure to write down the values of all the resistances or capacitances etc. that you use for your circuits in your notebook.
- If you are unsure of what to do, don't hesitate to ask!

Chapter 2

Experiments

2.1 Get familiar with the transformer and measurement devices

Measure the voltage and the frequency of the transformer's output, first with the multimeter and then with the oscilloscope.

2.2 Calculate the short-circuit protection resistance

Calculate the minimal resistance that has to be put between the terminals of the transformer for it not to be damaged. Use the specifications of the transformer, which are printed directly on it. Mind that VA (volt–ampere) is actually a watt.

From now on always connect your circuits to the transformer through the short-circuit protection resistor. In this way you will not break it when you accidentally make a short-circuit.

2.3 Measure the U-I characteristics of the source

Measure the output characteristics of the source (the U-I curve, voltage vs. load) using RMS voltage and current. Do not bypass the protection resistance! Is the output resistance constant throughout the load? How big it is? What part of it is the inner resistance of the transformer?

The U-I curve is the first basic measurement that you will be doing for various sources. It will not always be as simple as in this case. A good constant voltage source has the U-I curve flat in a wide range of loads. The more flat it is and the wider the range, the better.

2.4 Half wave rectifier

Use a diode to construct a half-wave rectifier. Measure the input and output voltage with an oscilloscope. Compare the two qualitatively and quantitatively.

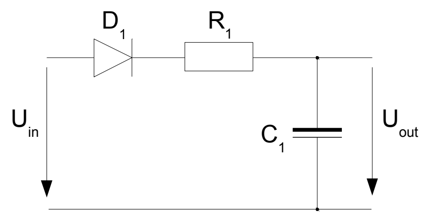

Figure 2.1: Half wave rectifier with a smoothing capacitor C_1 and short circuit protection R_1

A capacitor can be used to smooth the output voltage when connected as in Fig. 2.1. Use the oscilloscope to observe this.

Use a potentiometer to adjust the load on the power supply that you have just build. Note how the shape of the output voltage waveform changes when you change the load. Can you explain it? Experiment with several values of C_1. Once you get yourself familiar with the circuit, measure the output voltage waveform for different loads, keeping the C_1 constant. Then measure for several values of C_1 keeping the load constant.

Characterise the source for several values of C_1: Measure the output voltage and the ripple as the function of load. What is the output resistance? Does it depend on the load?

A useful approximation of the ripple of a rectifier with a smoothing capacitor is

$$U_{\text{r,pp}} \approx \frac{I_{\text{out}}}{f C_1} \; . \tag{2.1}$$

where f is the frequency of the AC voltage and I the load. Check when does this approximation hold.

2.5 Full wave rectifier

Take three additional diodes and replace the half-wave rectifier with a full-wave one, as shown in Fig. 2.2. Measure the input and output voltage with an oscilloscope. Compare the two, and the output of a half-wave rectifier, qualitatively and quantitatively.

Characterise the power supply in the same way you did for the half-wave rectifier. This time the ripple approximation is:

$$U_{\text{r,pp}} \approx \frac{I_{\text{out}}}{2 f C_1} \; , \tag{2.2}$$

For further measurements you can replace the four individual diodes with a single component full-wave rectifier. Also settle on the best value of C_1 to use from now on.

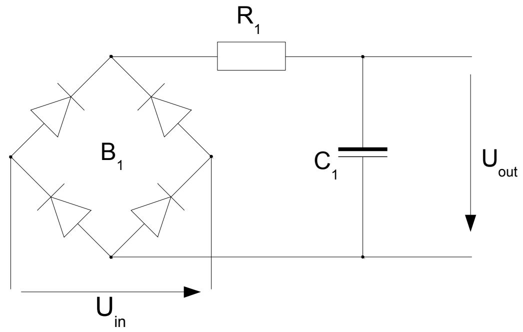

Figure 2.2: Full wave rectifier with smoothing capacitor C_1 and short circuit protection R_1

2.6 Voltage stabilisation – Zener diode

The voltage on a Zener diode is constant when a proper reverse bias current is applied to it. You can use the property to adjust and stabilise the output voltage of your source.

First you need to understand how to properly bias a Zener diode. In the data sheet you will find two important values. The *test current* is the bias current that the manufacturer used to measure other quantities in the data sheet. If you exceed the *admissible Zener current* the diode will permanently break. The values are different for different diodes. Remember, that you can use a multimeter to verify whether a diode is not broken.

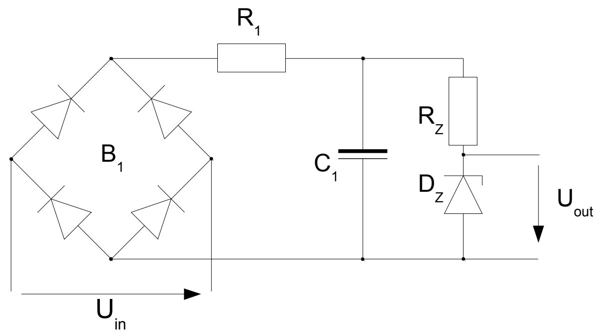

Figure 2.3: Full wave rectifier with smoothing capacitor C_1, short circuit protection R_1 and Zener diode stabilization

Add a Zener diode to your power supply, as shown in Fig. 2.3. Choose R_Z so that the diode is properly biased. It is a good idea to verify your calculations by directly measuring the bias current with a multimeter. Characterise the power supply which uses the voltage on the Zener diode as the output for the three available Zener diodes (3.6V, 5.6V and 12V). Remember to adjust R_Z each time! Can you explain the shape of the U-I curve? What is the most useful range of loads? What is limiting the region? To answer these questions it will help you to observe the output on the oscilloscope while you change the load. Also, what is the output resistance in the useful region? Have you improved you power supply by using a Zener diode?

2.7 The transistor - side tasks

To further improve your power supply you are going to use a transistor. It is just as hard as it is useful to develop an intuition for the operation of a transistor. And there is no better way to develop an intuition then to experiment with the next three side task circuits.

2.7.1 Current amplification (the transistor man)

Build the circuit in Fig. 2.4 where you can regulate the base current with a potentiometer. Take great care to identify the legs of the transistor (the information is in the data sheet) and then properly connect it. Measure I_C and I_B with multimeters. How does the $I_C(I_B)$ relation look like?

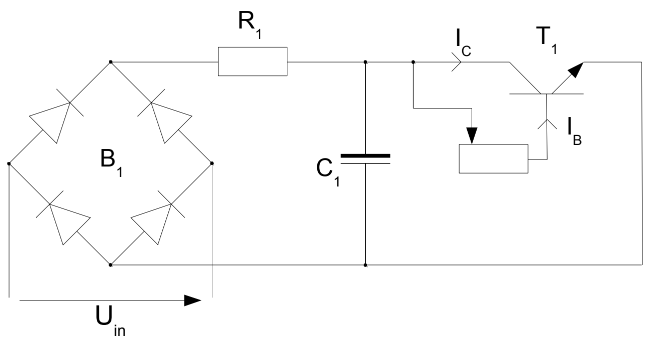

Figure 2.4: Current amplification of a transistor (the transistor man).

2.7.2 Current limit

Add another R_1 resistor to reduce the I_{CE} current, building the circuit in Fig. 2.5. How does the $I_C(I_B)$ relation look like now?

2.7.3 Buffer (emitter follower)

Use a potentiometer to build an adjustable voltage divider that defines the potential at the base of the transistor (Fig. 2.6). How does the relation $U_E(U_B)$ look like? Remember, that a conducting diode has a forward voltage drop of ≈ 0.6V.

A buffer is a useful building block for circuits. Its operation may seem to be pointless, but only at the first look. Remember, that the $I_C = h_{FE}I_B$ relation holds: the base current is several hundred times smaller then the collector current. That means that

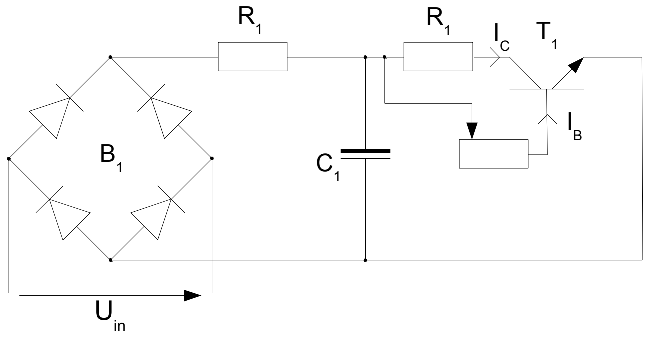

Figure 2.5: Current limit of a transistor.

there is very little load on the potentiometer, even though it controls a voltage potentially heavily loaded with current. Can you already think how to use a buffer to improve the power supply?

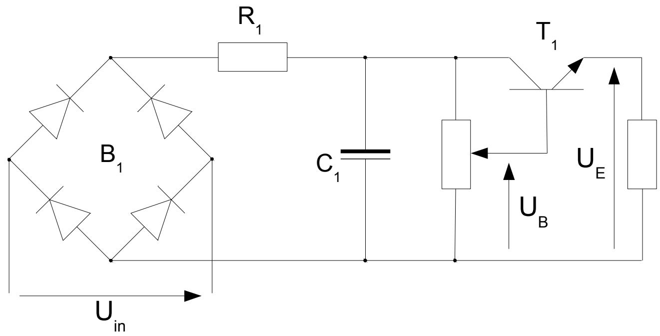

Figure 2.6: Buffer (emitter follower).

2.8 Zener diode buffered with a transistor

Incorporate a buffer referenced to the voltage on the Zener diode into the power supply, as shown in Fig. 2.7. If you observe fast oscillations on the output, called *ringing*, use a small non-polar capacitor C_2 to prevent them.

Repeat the observations and measurements that you did before, again for all three diodes. Compare to highlight the change that the buffer has made.

2.9 Active short–circuit protection

Using a series resistor is a simple, but not an effective mean for short–circuit protection. The resistance R_1 always dissipates quite a bit of power. It would be more clever to

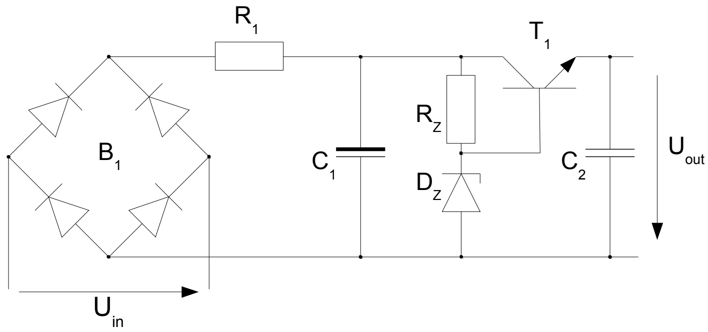

Figure 2.7: Full wave rectifier with smoothing capacitor C_1, short circuit protection R_1, Zener diode stabilization and transistor

dissipate significant power only in an event of a short–circuit. You can leverage properties of a constant current source to achieve just that.

2.9.1 Constant current source

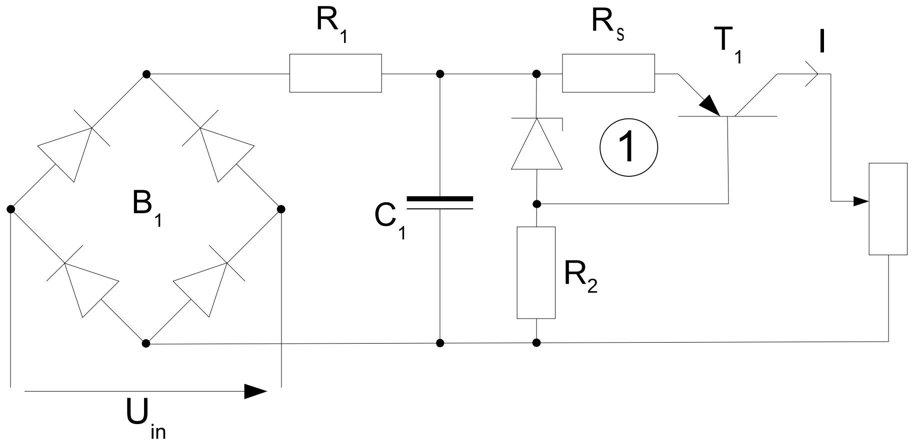

Figure 2.8: Contstant current source.

Take a look at the circuit in Fig. 2.8. It is a bit complicated to analyse, because it uses a transistor in a feedback loop to fix the collector–emitter current I_{CE}. The feedback compares voltage drop on the Zener diode to the one on the shunt resistor R_S (in general, a shunt resistor is one, on which a voltage is measured to determine the current flowing through it). It works in the following way: as soon as the current I drops, the voltage drop on the shunt resistor R_S is smaller, causing a higher base current, which in turn increases the current I. If the current I should rise, the voltage drop on the shunt resistor R_S increases, which decreases the base current and, in turn, lowers I. The Zener diode effectively fixes the voltage on the shunt resistor. Following the Kirchhoff law for the small loop (1): $-IR_S - 0.6V + U_Z = 0$, where U_Z is the voltage on the Zener diode. Rearranging gives the nominal current of a constant current source:

$$I = \frac{U_Z - 0.6}{R_S} \tag{2.3}$$

Build the circuit for a current of $\approx 100\,\mathrm{mA}$. The value of R_2 should be chosen such that the current through the Zener diode is stable. That is, it should not depend much on the base current. This is to make sure that the voltage drop over the diode, which is ideally constant but in reality stilll depends weakly on the current, is as constant as possible. In this case, you may choose R_2 such that $\sim 80\%$ of the Zener diode current flows through it. How does the current I react when you adjust the load potentiometer? By adjusting the load potentiometer you change the output voltage. Measure the output current as a function of the output voltage (i.e. the voltage over the potentiometer in Fig. 2.8). Can you determine the two regions of operation: constant current and saturation?

2.9.2 Improved power supply

How can use use a constant current source for a short–circuit protection? Determine the nominal current of a constant current source for protecting the transistor in your power supply. You can choose different combinations of the shunt resistance and diode to achieve the same current. Decide which one is the best for your power supply.

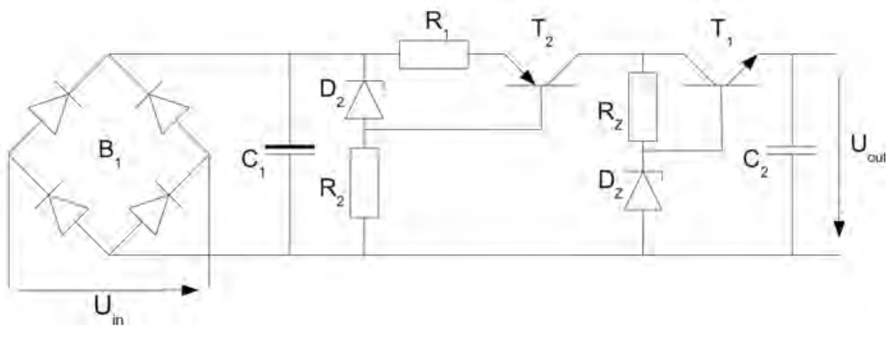

Figure 2.9: Full wave rectifier with smoothing capacitor C_1, active short circuit protection and a buffered Zener diode stabilization.

Return to your circuit from Sec. 2.6 and replace the protection resistor with an active short–circuit protection, building a circuit in Fig. 2.9. Characterise the source for one of the Zener diodes setting the output voltage (D_Z). Think which one would be the most interesting to measure. Compare the results to the performance of the version with a plain resistor as a short–circuit protection.

2.10 Integrated circuit: LM78xx

It has been very instructive to build the power supply from basic electronic components but, as you may have guessed, higher–level building blocs are available on the market. In particular, fixed voltage regulators LM78xx (the last two digits indicate the voltage) may be used instead of the buffered Zener diode. They go beyond just integrating the components that you have used in a single package, so you may expect that they will improve the power supply.

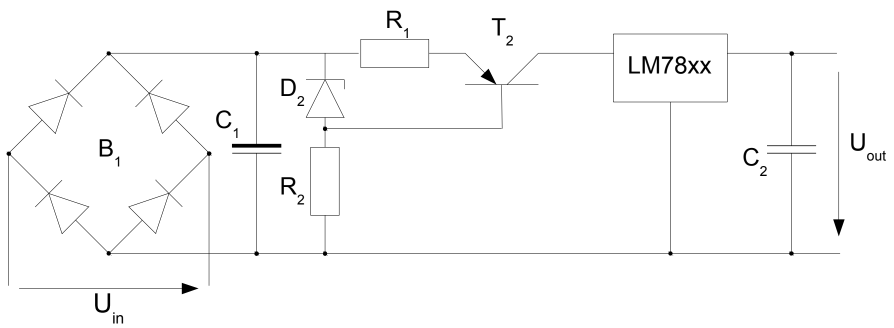

Figure 2.10: Full wave rectifier with smoothing capacitor C_1, active short circuit protection and LM78xx regulator.

Build the circuit as in Fig. 2.10. Look in the datasheet to properly identify the legs of the component. Check twice! Characterise the power supply and compare it to the one with a buffered Zener diode.

2.11 Adjustable voltage stabilisation: LM317

So far you fixed the output voltage of your power supply at the point of choosing the parts, either a Zener diode or the LM78xx. You can use the LM317 part to make the output adjustable.

Replace voltage regulator with a LM317. Check the datasheet and identify the legs. Then check again. Use a potentiometer to adjust the potential on it's adjustment leg. Should you use a potentiometer with a big or a small resistance? Characterise the voltage source for several output voltages. Compare its performance to your previous power supplies.

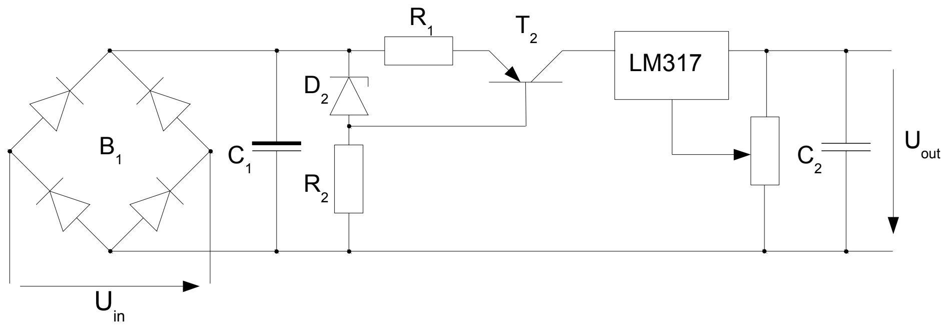

Figure 2.11: Full wave rectifier with smoothing capacitor C_1, active short circuit protection and LM317 variable regulator

Appendix A

Quantisation Error

When using a multimeter and an oscilloscope it may seem to be difficult to assess uncertainty of the measurements. It is not, however, impossible.

There are two situations that can occur when reading out the measurement from a device: either the reading is steady or it is not. In the first case the precision is limited by the number of digits of the display. Then the value includes an *quantisation error*. Uncertainty of this type is not the easiest one to deal with statistically, but can be estimated to be LSD/$\sqrt{12}$, where LSD stands for the least significant digit [1]. Make sure to always write down all displayed digits to always be able to identify the least significant one.

When the readout is fluctuating, estimate the amplitude of the fluctuation. Remember that the error-bars are usually defined to cover the 68% confidence level region, rather then the whole of it. To take the measurement you can freeze the readout using the HOLD button to make sure it is a random sample from the fluctuation.

Bibliography

[1] URL: `https://en.wikipedia.org/wiki/Quantization_(signal_processing)`.

[2] Paul Horowitz and Winfield Hill. *The Art of Electronics, Third Edition*. Cambridge University Press, 2015.

[3] Donald A. Neamen. *Semiconductor Physics and Devices: basic principles*. McGraw-Hill Higher Education, 2003.

[4] Ben G. Streetman and Sanjay Banerjee. *Solid State Electronic Devices*. Pearson Prentice Hall, 2006.

[5] Ulrich Tietze and Christoph Schenk. *Halbleiter-Schaltungstechnik*. Springer, 2002.