Crystal Clear Electronics

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20 - Voltage Regulators, Current Limiters with Transistors

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In this section you can learn more about the structure and operation about voltage regulators previously used in the curriculum and about simple current limiters.

Voltage regulators are among the most-used electronic components. Generally, circuits need a stable supply voltage at varying load conditions for current operation be it a microcontroller-based control unit or an analogue amplifier. Of course, when choosing a voltage regulation technique, one must take the circumstances of the specific circuit into account.

At the start of the design process we have chosen that our circuit will be supplied from a battery or from a fixed power supply. The next step is to design the power plan according to the requirements of the circuit. Take a look at a car for example: The voltage of a car battery varies between around 9 V and 14 V with state of charge and load conditions. It will be different if it is almost full and the alternator is charging, or if we have just tried to start our car several times on a cold morning to no avail. Therefore, the electric system of a car is designed in such a way that they work if the supply voltage is between 8 V and 16 V. Nobody would be happy if the loudness of the hi-fi system or the brightness of the headlights in their car would change with battery voltage.

Another example is that we can even damage the microcontroller we have used in the previous chapters if we fail to meet the supply voltage specification in the datasheet. A microcontroller designed for 5 V operation usually can work according to specification if the supply voltage is between 4.5 V and 5.5 V. But how can we turn 14 V into 5 V?

A resistor divider can easily create 5 V from a 14 V supply. The problem is, as soon as current starts to flow (a load is applied to the 5 V output), the voltage decreases proportional to the current. The other, severe problem is that the output voltage is dependent of the input voltage. If the 14 V becomes 9 V on the input, the output 5 V will also decrease accordingly.

The voltage produced by a resistor divider can only be considered constant if the input voltage is already stable and no load is applied to the output.

In order to create a constant output voltage regardless of the input voltage, semiconductor components are required.

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PARALLEL POWER SUPPLIES, ZENER-DIODE

We have already learned about diodes in the previous chapter, and we also know that they cannot withstand and arbitrarily high reverse voltage. The reverse voltage where a diode starts to conduct backwards is called the reverse breakdown voltage. This voltage is usually high in regular diodes (50 V or above), but there are special diodes called Zener-diodes where this voltage is precisely known and manufactured to be a certain voltage. These diodes are designed to work in the breakdown region.

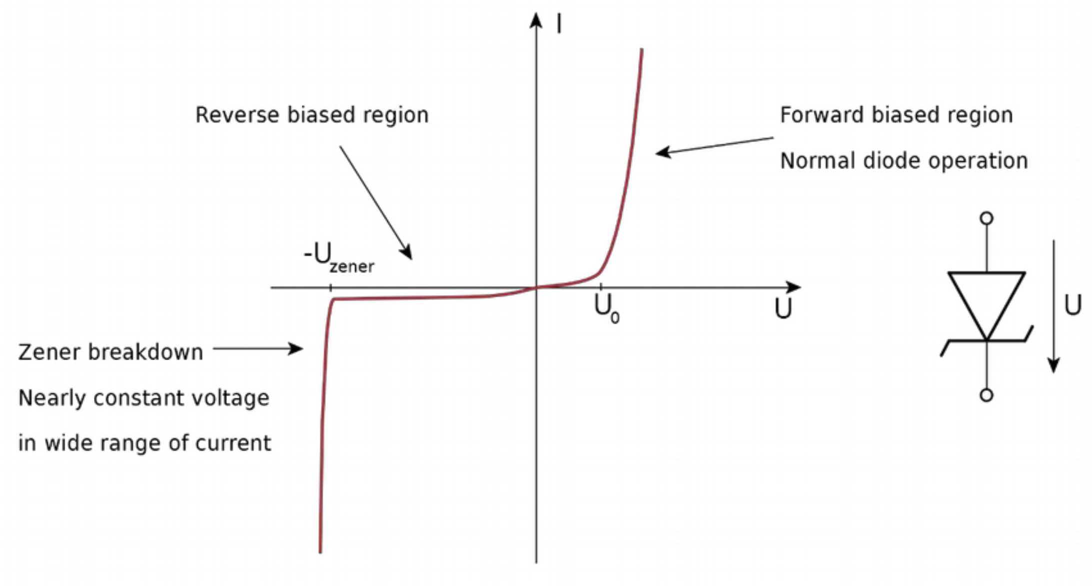

Figure 1 – Current-voltage curve of a Zener diode

Upon reaching the reverse breakdown voltage ($-U_{Zener}$ in the figure above) the curve becomes very steep, the voltage in that region almost doesn't change. This way, this phenomenon can be used for voltage regulation.

Connect a Zener-diode in series with a resistor to limit the current:

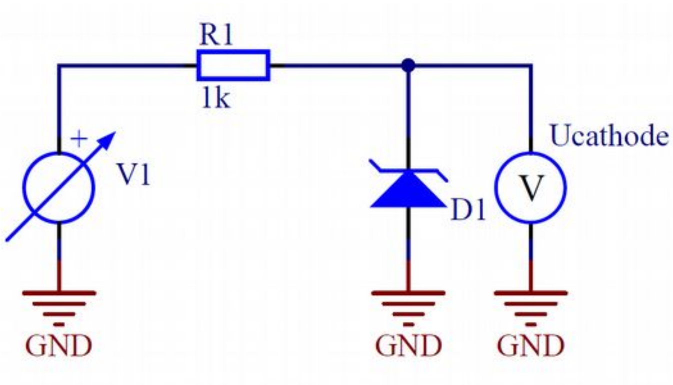

Figure 2 – Zener-diode with a resistor in series

If the input voltage V_1 is higher than the breakdown voltage of the Zener-diode, the voltage drop on the diode will always be the breakdown voltage, and the rest will drop on the resistor.

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If we apply a load to the output of the circuit, then current will flow through it, reducing the current flowing through the diode. The diode can only act as a voltage regulator as long as current is flowing through it, in other words until the load is not too high.

If we model the simply circuit above in a simulator, and set the voltage of the voltage source to sweep from -4 V to 16 V, then the output voltage will look like the following (U_{output} or $U_{cathode}$), which is the voltage of the Zener-diode.

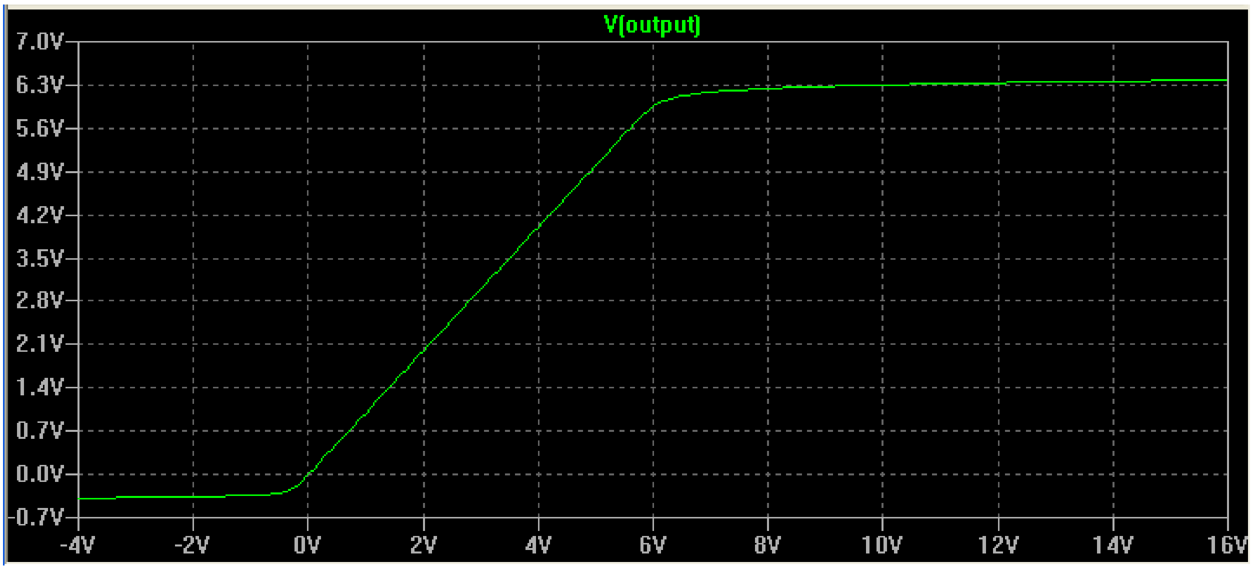

Figure 3 – Cathode voltage of the Zener diode

You can see that below 0 V the diode behaves as a normal diode (because negative voltage means that the ground is at a higher potential, so the voltage applied to the diode is a forward voltage). The voltage drop on it is the regular forward voltage of a diode or around -0.6 V. From 0 V to 6 V the voltage equals the supply voltage, so there is no current flowing through the diode. Then, as approaching 6.3 V, the voltage starts to flatten and approach a stable 6.3 V even if the supply voltage is increasing beyond 7 V. This shows that the reverse breakdown voltage of this Zener-diode is 6.3 V.

Zener diodes are manufactured with many different breakdown voltages, and we can easily choose the parameters that suit our application.

This type of voltage regulation, where the regulating component is placed parallel with the load, is called shunt voltage regulation.

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The schematic with the load added looks like this:

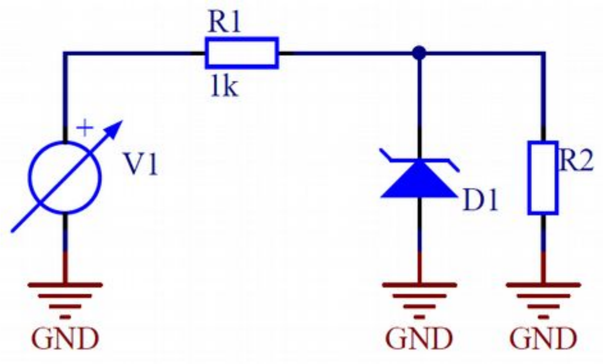

Figure 4 – Shunt voltage regulator

Because the Zener-diode is added, the load marked with R_2 will see constant voltage. The current flowing through R_1 will be shared by the diode D_1 and the load R_2.

In the voltage range where the load does not influence the output voltage, the current flowing through R_1 does not depend on the magnitude of load placed at R_2. Such a circuit consumes the same amount of power regardless whether the load is on or off. This feature is both an advantage and a disadvantage. An advantage, because the required current is always the same. A disadvantage because at low loads the efficiency is very poor. Another advantage is that it is difficult to imagine a simpler circuit, it consists of only two components.

Now calculate the load at which the D_1 Zener diode can provide a stable supply voltage. (The load is symbolized by the R_2 resistor.) Because of Kirchhoff's first law, the sum of the currents flowing through D_1 and R_2 will flow through R_1, so

$$I_{R1} = I_{D1} + I_{R2}$$

If the voltage source marked with V_1 has a voltage of 12 V and the voltage of the D_1 Zener-diode is 6.3 V, then the voltage across the resistor R_1 will be 5.7 V, so the current of R_1 will be

$$\frac{5.7\ [\mathrm{V}]}{1000\ \ [\Omega]} = 5.7\ [\mathrm{mA}]$$

If R_2 is chosen in the example circuit so that the current flowing through it is close to 5.7 mA, then the voltage will not be regulated anymore and the supply voltage of R_2 will fall below 6.2 V because in order the voltage to remain stable, current must flow through the diode. Usually this value is not stated in the datasheet as a minimum current but as a recommended current. If we look at the datasheet of our diode, it contains the Zener-voltage at three different currents: 1 mA, 5 mA and 20 mA. To keep the Zener-voltage within the range given in the datasheet, at least 1 mA of current must be flowing through the diode.

Also look at the maximum current that can flow through the diode without destroying it. To calculate this, you need to read the Maximum Ratings section of the datasheet (page 1).

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MAXIMUM RATINGS

Rating	Symbol	Max	Unit
Total Power Dissipation on FR−5 Board, (Note 1) @ T_A = 25°C Derated above 25°C	P_D	225 1.8	mW mW/°C
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	556	°C/W
Total Power Dissipation on Alumina Substrate, (Note 2) @ T_A = 25°C Derated above 25°C	P_D	300 2.4	mW mW/°C
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	417	°C/W
Junction and Storage Temperature Range	T_J, T_{stg}	−65 to +150	°C

Maximum ratings are those values beyond which device damage can occur. Maximum ratings applied to the device are individual stress limit values (not normal operating conditions) and are not valid simultaneously. If these limits are exceeded, device functional operation is not implied, damage may occur and reliability may be affected.

1. FR−5 = 1.0 X 0.75 X 0.62 in.
2. Alumina = 0.4 X 0.3 X 0.024 in, 99.5% alumina.

Figure 5 – Maximum Ratings Table of the Diode
Source: ON Semiconductor, MMBZ5221BLT1 datasheet

Since the datasheet is for the whole diode family, we will not find a maximum current, only the maximum power, but from that and the Zener voltage we can easily determine the current. Two values are given for the maximal power. The one we need is the one with the standard circuit board material (FR board), 225 mW. The other one is for when the diode is mounted on an aluminium heatsink.

$$I_{max} = \frac{P_{max}}{U_{Zener}} = \frac{0.225\ [W]}{6.2\ [V]} = 0.036\ [A]$$

Based on the datasheet these values are valid for an ambient temperature of 25 °C. Of course, we can determine how the maximum allowed power changes at higher temperatures based on the thermal conductivity. A good rule of thumb is to only allow 50% of the maximum current, which is 18 mA in this case.

If the voltage of V_1 is 12 V then the 5.8 mA I_{R1} current is well within the 18 mA limit and with a 1 mA minimum I_{D1} current, 4.8mA is left for the load R_2.

In our example, V_1 is a car battery, so the optimal voltage is 12 V. Let's also calculate what happens at the boundary values of 9 V and 14 V.

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If $V_1 = 14\ [\mathrm{V}]$ then we need to calculate whether the current flowing through R_1 is less than 18 mA or not. Based on previous calculations:

$$I_{R1} = \frac{14\ [V] - 6.2\ [V]}{1000\ [\Omega]} = 7.8\ [mA]$$

which means we are well within the limit.

Now also calculate how much current is left for the load if $V_1 = 9\ [\mathrm{V}]$ and at least 1 mA is flowing through diode D_1!

$$I_{R1} = \frac{9\ [V] - 6.2\,[V]}{1000\ [\Omega]} = 2.8\ [mA]$$

plugging this into the formula $I_{R1} = I_{D1} + I_{R2}$, and assuming $I_{D1} = 1\ [\mathrm{mA}]$:

$$I_{R2} = 1.8\ [mA]$$

What does this mean? It means that if we want our circuit to work anywhere between 9 V and 14 V, the load must consume less than 1.8 mA. Of course, we can improve this number by choosing a smaller R_1 but then we have to use a higher-powered Zener-diode too. You can see that this voltage regulation method wastes a lot of power, because a lot of energy is dissipated on R_1 and D_1. We need a circuit that does not change the maximum load current by this much if the input voltage changes. This is the problem solved by serial voltage regulators.

Such circuits are, for example, linear power supplies which add transistors to the simple Zener-diode.

Series Voltage Regulators

The main idea behind series voltage regulators is to connect a circuit with variable resistance in series with the load. By adjusting the resistance of this element, we can control the voltage drop on it, and make sure that the load sees a constant voltage.

The advantage of a series voltage regulator is that the current flowing through the circuit is the same as the load current, since they are connected in series. Compare this to the parallel voltage regulator from the previous section, which used the maximum current regardless of the load. Because the current usage is lower it results is a much higher efficiency. You can see the block diagram of a similar device in the next figure.

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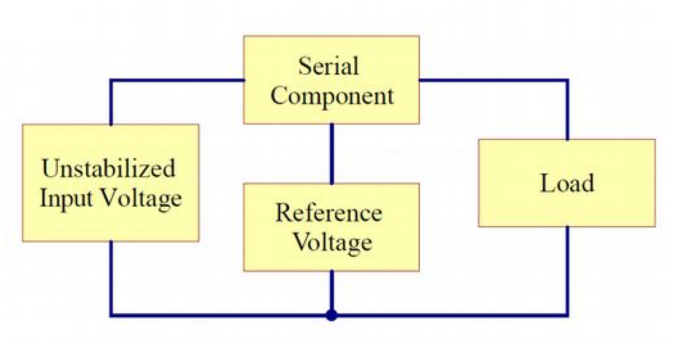

Figure 6 – Schematic structure of a series voltage regulator

IMPLEMENTATION WITH DISCRETE COMPONENTS

One of the simplest implementations of this concept is the emitter follower series voltage regulator:

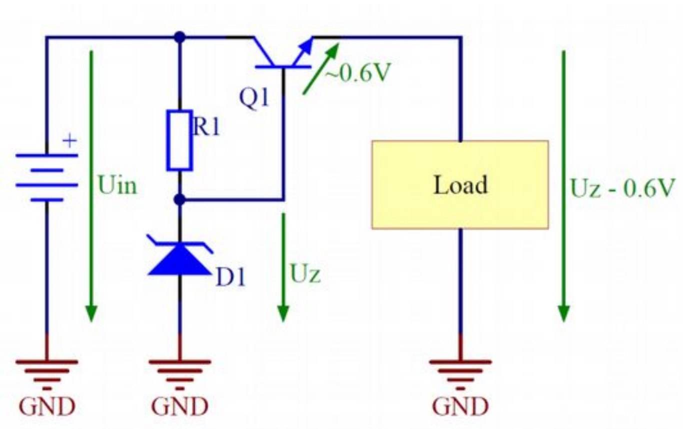

Figure 7 – Emitter follower series voltage regulator

In this circuit, the variable resistance is implemented by the transistor used in the emitter follower mode.

The load sees the voltage of the Zener-diode, minus the base-emitter voltage of the transistor.

Choosing the right transistor for such a circuit is not difficult. If we know the maximum current required by the load, we can calculate the required base current. To do this, the load current must be divided by the transistor gain (can be found in the transistor datasheet as h_{FE}). So:

$$I_b = \frac{I_{load}}{h_{FE}}$$

The next step is to select a resistor that will adjust the current flowing through both the Zener-diode and the transistor base current. Here's how to calculate it:

$$R = \frac{U_{in} - U_Z}{I_Z + K \bullet_b I}$$

Where U_{in} is the input voltage, U_Z is the Zener voltage, I_Z is the Zener current, I_b is the transistor base current, and K is a number that ensures that the system has some reserves, in this case let it be 1.5.

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On the load, the Zener voltage will appear minus the transistor’s forward voltage.

These series voltage regulators have significantly better efficiency than the solutions discussed previously, if the difference between the input and output voltages is not much greater than the transistor’s forward voltage.

Most of the time, we do not build our voltage regulators from discrete components, but instead we choose a ready-made solution integrated into a single component.

IMPLEMENTATION WITH INTEGRATED CIRCUITS

For general purposes, one of the most obvious choice is the 78xx component family. These have already been mentioned in earlier chapters of the curriculum. For example, the L78L33 with fixed output does not require any external component other than two capacitors to produce a 3.3 V output voltage. A schematic with the simplified internal structure of the component is shown in the following figure:

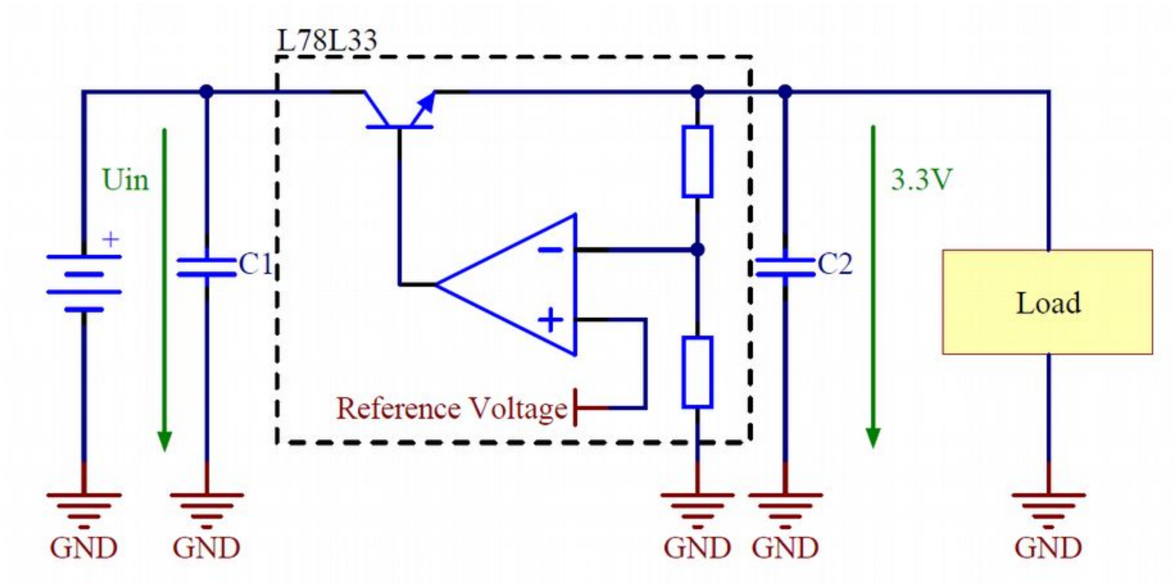

Figure 8 – Implementation of a voltage regulator with integrated circuits

The dotted line shows the case of the IC. The triangle is an operational amplifier, which as you can remember sets its output voltage (when there is no feedback) $U_{out} = A \bullet (U_+ - U_-)$ where A is the open-loop gain (typically 1000). Here, it acts as a comparator in the L78L33 because it compares the output voltage of the IC (divided by a resistor divider) with a reference voltage. This comparator controls the transistor acting as a variable resistor.

LDO REGULATORS

Typically, the 78xx family needs a higher input voltage than the output voltage by at least 1.5 V to function. What can we do if we want to power a 3.3V circuit, but our input voltage can vary between 5.0 V and 3.5 V, for example? At this point, the L78L33 will no longer be able to generate 3.3V for our circuit.

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Low Dropout Voltage Regulators, in short LDOs, provide a solution to this problem. LDOs are series voltage regulators that can provide controlled output voltage even when the input-output voltage difference is only 100 mV.

LDO's are identical in structure and usage to ordinary series voltage regulators. The difference comes due to the fact that the output has a FET instead of a bipolar transistor. This reduces the voltage drop and eliminates the need for a large voltage difference between the input and output. These components are slightly more expensive than their counterparts with higher dropout voltage, so you might want to use them only if you really need the benefits they offer.

Task A:

Build the example circuit below. Measure the output voltage, then connect an LED between the 5 V output and ground with a 330 Ωresistor in series. Let's see how much the output voltage has changed! You will find that the output voltage remains within 5 V ± 0.2 V.

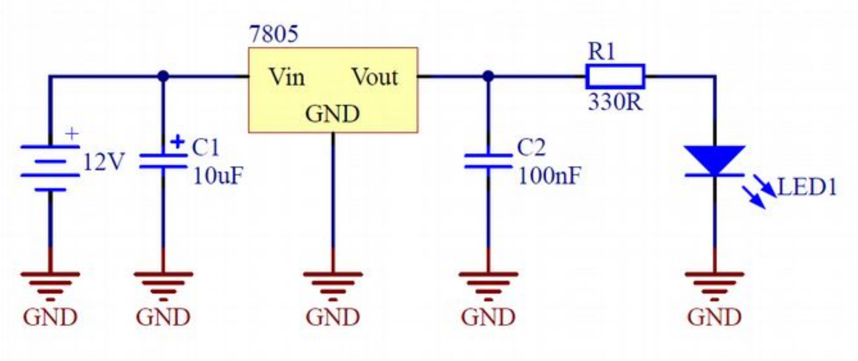

Figure 9 – The circuit to be implemented

CURRENT LIMITERS AND CURRENT SOURCES

The operation of current limiters and the current sources are very similar, in both cases it is a circuit that keeps the current at fixed value.

In different fields of application users have different goals in mind, hence the two names. The current limiter is protecting against the overloading a voltage source, while the term current source is used for a circuit which consumes a constant current (For example, this is the ideal way to drive an LED).

Why limit the current?

If the current consumption of our load increases significantly, it usually indicates an error and it can permanently damage both the load and even the power supply. Therefore, in most cases we would like to protect ourselves against this. The easiest way to protect our circuit is using a fuse. This solution is usable when the probability of a malfunction is low. If an error still occurs, we are forced to replace a component (There is an even more significant problem with the fuse: its speed. Sensitive digital circuits are easily destroyed by the time the fuse melts).

These problems are solved using an electronic current limiter.

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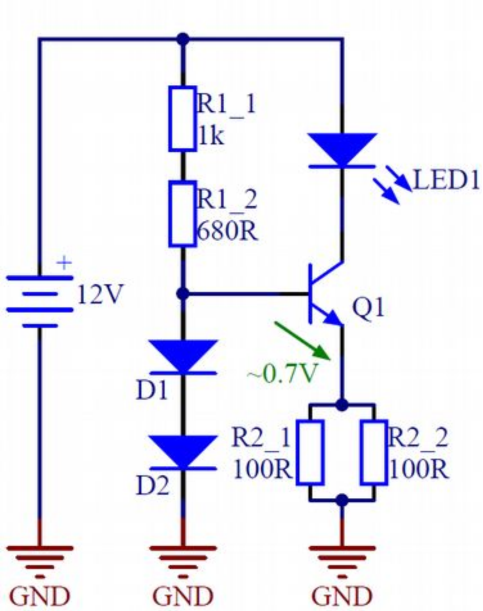
Task B: Driving an LED using current source

The circuit shown in the figure below is one of the simplest LED drivers using a current source. The next task is to build this circuit.



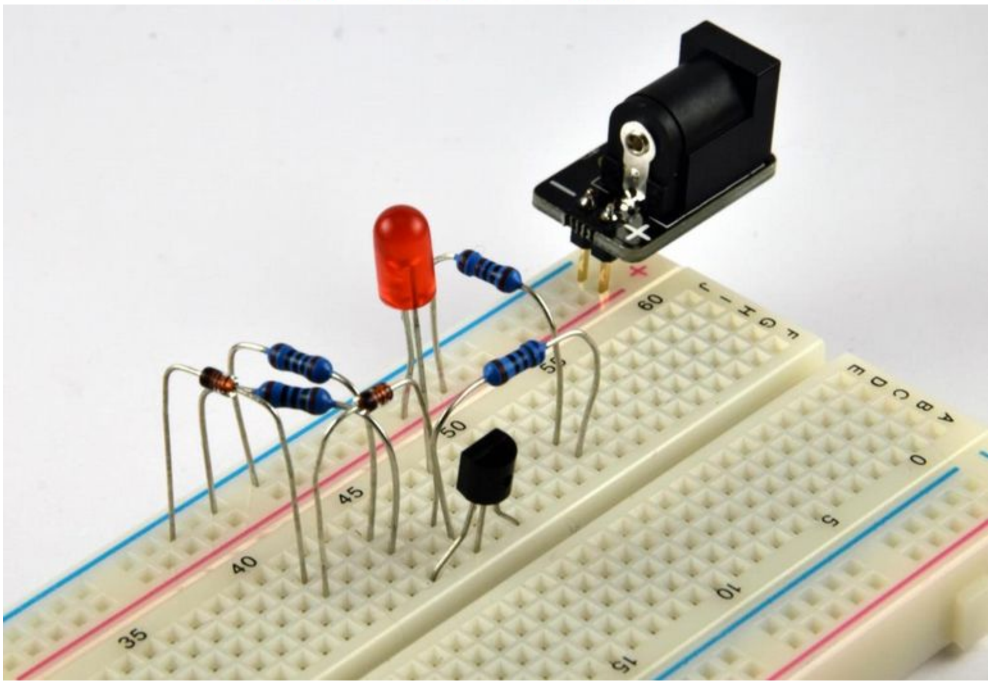


Figure 10 – Driving an LED using current source

This circuit is capable of driving LEDs requiring higher power, but we stick to low-current regular LEDs for now. To build the circuit you need one npn-transistor, one LED, two diodes, two 100 Ω resistors, one 1 kΩ resistor and one 680 Ω resistor.

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The two diodes are used to provide a near-constant voltage (1.4 V) between the transistor base and ground. Since the base-emitter voltage drop (U_{be}) is 0.7 V, the remaining 0.7 V will drop on the resistor R_2. As a result, the LED current can be calculated as:

$$I_{LED} = \frac{0.7\ [\mathrm{V}]}{R_2}$$

For example, if we have an LED that we want to drive with 20 mA, we should choose a 35 Ω resistor for R_2, and using a 50 Ω resistor will produce 14 mA of current. To get that, connect two 100 Ω resistors in parallel. Thus, 0.0098 W is dissipated on the resistor.

The next step is to define R_1. First, find the transistor current gain in the datasheet. This is 290 in case of the BC546B, so for a collector current of 20 mA, the base current must be $20\ [\mathrm{mA}] / 290 = 0.07\ [\mathrm{mA}]$ The diodes need an additional 2 mA to produce the expected voltage drop accurately. So R_1:

$$R_1 = \frac{U_{supply} - U_{diode}}{I_b + 2\ [\mathrm{mA}]} = \frac{5\ [V] - 1.4\ [V]}{0.07\ [mA] + 2\ [mA]} = 1.73\ [\mathrm{k}\Omega]$$

Since we do not have an exact 1.73 kΩ resistor, connect a 1 kΩ and a 680 Ω resistor in series to get 1.68 kΩ.

By powering the LED using the circuit built in Task A, a significant portion of the power is dissipated on the resistor. In case of a current source driver, the transistor plays the role of a variable resistor that changes its resistance depending on the voltage drop on it, so that the current flowing through it remains constant. We can even try this and measure it with other input voltages. It is important to note that in such a case, significant power is dissipated on the transistor. Therefore, the maximum heat transfer capability of the transistor must be taken into account when designing.

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Cut back on diodes

The following circuit provides a similar behaviour using two transistors instead of two diodes and a transistor.

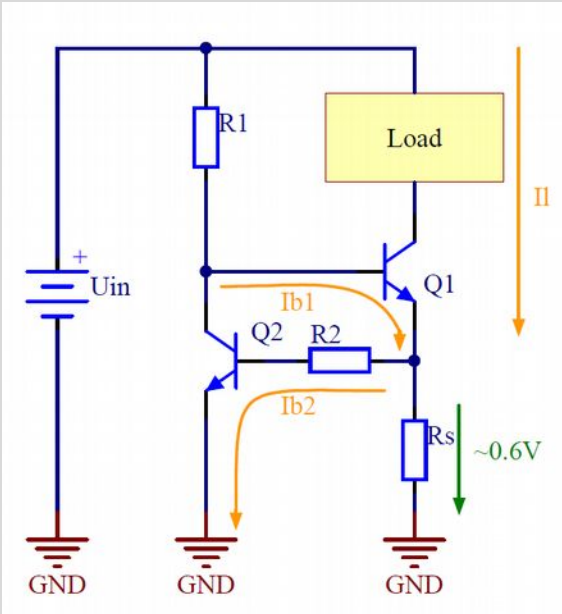

Figure 11 – Circuit diagram of a current limiter

Only the maximum allowable current can flow through the load. In the circuit, the R_1 resistor turns on the transistor marked Q_1, which will cause current to flow through the load. When the current flowing through R_s exceeds the designed value, Q_2 starts to turn on, which gradually turns Q_1 off, thus limiting the current. The function of the optional R_2 resistor is to limit the base current of Q_2. Due to its simplicity, this circuit can also be used to drive high-brightness LEDs.

CLOSING WORDS

During this chapter of the curriculum we learned about the basic operation of voltage regulators. Considerable amount of literature can be found in this area of electronics, so it is not surprising that this chapter of the curriculum is not exhaustive, its purpose is to awaken the reader's curiosity.

In the first section we got to know the simplest circuits based on the Zener-diode. From there we get to the LDOs with transistors and to the current sources. There is no mention of switching power supplies that can further improve efficiency, but if someone needs to improve the efficiency further, they will be able to learn about the subject on their own with the knowledge acquired in this chapter of the curriculum.

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