Electronics II.

Operational amplifier applications:

voltage and current regulators

(2021.3.23.)

Measurement aims:

Examination of voltage references, regulators and current generators realized using operational amplifiers. These are mostly low-current applications because of the opamp's limits.

In this guide the circuits to be measured are ordered in such a way so that they can easily be modified from each other, minimising the time needed for building. In the lab report it may be preferred to order the circuits according to their types, such as first voltage references and regulators and compare them to each other, then current generators and their comparison.

In this measurement, instead of entry questions, you have to present the homework solutions to the teacher to be able to start the measurement.

Before starting the measurements, don't forget to setup 30mA[1] current limit on the power supply unit! In some of the measurements you will have to change this limit, it will be indicated in the guide. After such a measurement set the limit to its original value.

Homework:
Look up the maximum ratings for the devices. The Zener diodes and bandgap reference (Izmax), the opamp (V_{outmax}, I_{outmax}) and the transistor (I_C and V_{CE} max, mostly). These values may be needed for the homework calculations and for comparison with the measurement results, therefore bring these values with you to the lab. During the measurement, keep the operating parameters within these limits! (Of course the voltage and current limit we setup on the power supply is designed for this purpose, but please check if this will be true.)

Components

- 1× LM258 or uA741 opamp IC (check at start of measurement which type you have!)
- 1× BC301 NPN transistor
- 1× ZPD5.1 or BZX5V1 Zener diode (5.1V)
- 1× LM385-2.5 or LM285-2.5 2.5V bandgap reference IC
- 1× 100kΩ
- 2× 10kΩ
- 1× 20kΩ
- 1× 3kΩ
- 1× 1kΩ
- 1× 1kΩ potmeter
- 1× 10kΩ potmeter

[1] The opamp should have about 20…25mA built-in limit, that's why we set our limit only slightly higher (this way you can see the opamp's limit in action, should you wish to do so). Please note that the opamp's built-in limit only refers to its output current. It doesn't protect the whole opamp. For example wrong connection of power supply can still damage it etc.

Measurement and calculation exercises

1) Comparison of Zener diode and band-gap reference

The *bandgap reference*, also called *micropower voltage reference*, is an integrated circuit made up of bipolar transistors, which behaves similar to a Zener diode. Compared to the Z-diode, it has a more precisely determined breakdown voltage, lower dynamic resistance (r_Z) and lower temperature dependence, thus more precise voltage references can be realised using them. Their reference voltage is usually 1.2V or 2.5V. Also their minimal current is much lower than that of Z-diodes. For the LM285 this is about 10µA (compared to a few mA for Z-diodes). Thus we can realise circuits with lower consumption, especially important if operating from batteries; also the self-heating is much smaller (further decreasing the effect of temperature dependence). The maximum reverse current of this IC is specified at about 20mA. On the other hand, Zener diodes have a larger interval of possible breakdown voltages and can have much larger maximal currents, thus are more appropriate for voltage limiting and protection applications.

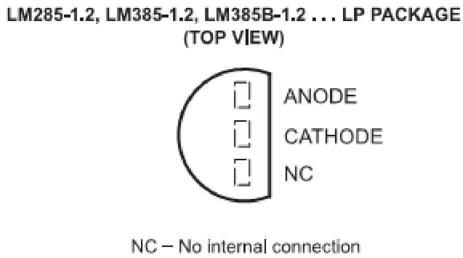


Figure 1. Pinout of LM285 reference IC in TO-92 package (top view)

Homework

1.1
Find the datasheet of ZPD5.1 or BZX5V1 diodes and the LM285-2.5 reference IC. Look up the following parameters: minimal operating (reverse) current, dynamic resistance (or current dependence of breakdown voltage), temperature dependence of breakdown voltage, tolerance of breakdown voltage. These values may be needed for the homework calculations and for comparison with the measurement results, therefore bring these values with you to the lab.

Measurements

1.2
Measure the voltage and current of the Zener diode and the LM285 bandgap reference in at least two points (in the breakdown region). For example I_{Z1}=5mA, I_{Z2}=10mA. Find the dynamic resistance (r_Z) from these two points! The band-gap reference's dynamic resistance is very low (lower than one Ohm), therefore try to measure very precisely and choose your two points sufficiently far away (within the minimum and maximum limits).

Reminder:

$$r_z = \left| \frac{V_{z2} - V_{z1}}{I_{z2} - I_{z1}} \right|$$

2) Simple voltage reference (from voltage follower circuit)

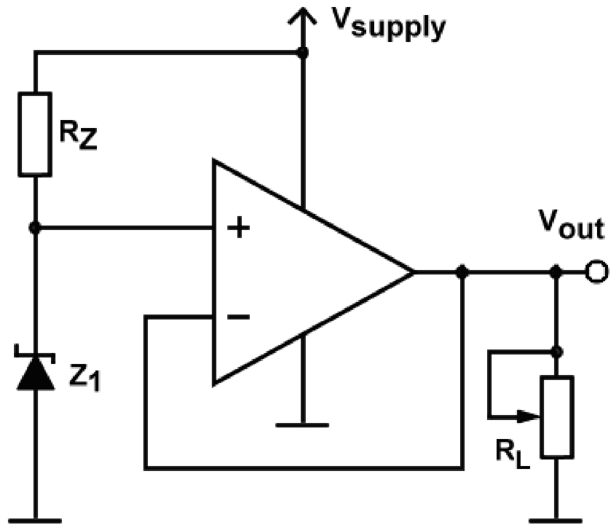


Figure 2. Simple voltage reference

Parameters: V_{supply}=10V ; R_Z=1k ; Z_1=ZPD5.1 ; R_L=10k potmeter
The voltage follower circuit can be used if we need a voltage reference equal to the breakdown voltage of the Zener diode. The low output resistance of the opamp means the output voltage depends very little on the load and the high input resistance of the opamp means the Zener diode is not loaded.

Measurements:

2.1
Build the circuit and set the potmeter to maximum. Measure the output voltage (V_{out}) and the Zener diode's voltage (V_Z). Compare these values. (Remember to use 0.001V precision for measurements.)

2.2
Find the minimal load resistor. For this measurement, setup **80mA** current limit (because we want to see the effect of the opamp's own current limit). Start decreasing R_L and monitor V_{out}. We shall define R_{Lmin} when V_{out} drops to about 90% of its nominal value (this is of course a somewhat arbitrary value, chosen for easier measurement). Measure the output current at this point! (Try to do this measurement point as quickly as you can, to minimise the self-heating.) Compare the measured value with the maximum ratings from the datasheet of the opamp (such as „output current" or „short circuit output current").
Set the 20mA current limit again after this measurement!

2.3
Examine the dependence of V_{out} on the supply voltage. Set R_L to maximum. Measure V_{out} (precisely) at V_{supply}=10V and at V_{supply}=19V (*as the supply unit can't always go up to 20V*). Find the relative change:

$$\frac{\Delta V_{out}}{\Delta V_{supply}} \left[\frac{mV}{V}\right]$$

What happens when you further decrease the supply voltage (start from 10V)? What is the minimal supply voltage at which the output is still at its nominal value? What is the reason for this minimum?

3) Adjustable voltage reference

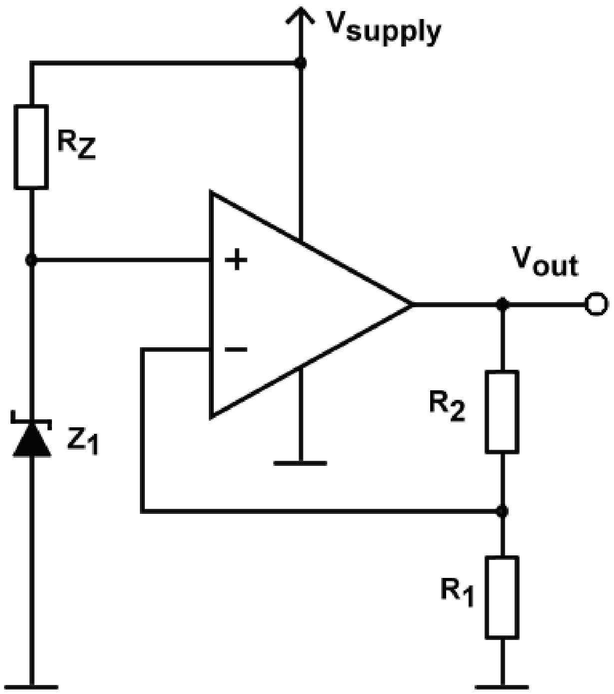


Figure 3. : Voltage reference circuit with adjustable output

Modify the previous circuit using a voltage divider as a negative feedback. The resulting circuit is actually a DC non-inverting amplifier (with constant input).

Parameters:: V_{supply}=20V ; R_Z=3k ; Z_1=ZPD5.1 ; R_1=R_2=10k

Homework:

3.1
Calculate the operating point values (V_Z, I_Z, V_{out}). What is the maximum output voltage we could achieve (by changing the ratio of R_1 to R_2) ?

Measurements:

3.2
Measure V_Z and V_{out} nominal (unloaded) and compare with the calculations.

3.3 Find the dynamic output resistance. Apply a 10k potentiometer as load R_L similarly as in the previous circuit. Measure the output voltage and current in two (sufficiently distant) points. For example, R_{L1}=10k (max) for one point, I_{out2}=10mA for the other (keep within the current limit). The output resistance is

$$r_{out} = \frac{|\Delta V_{out}|}{|\Delta I_{out}|}$$

3.4
Using the resistors available try different R_1 to R_2 ratios and the output voltages you can gain by them. Try one combination when the output voltage „would be” greater than the supply voltage.

4) Current generator with floating load

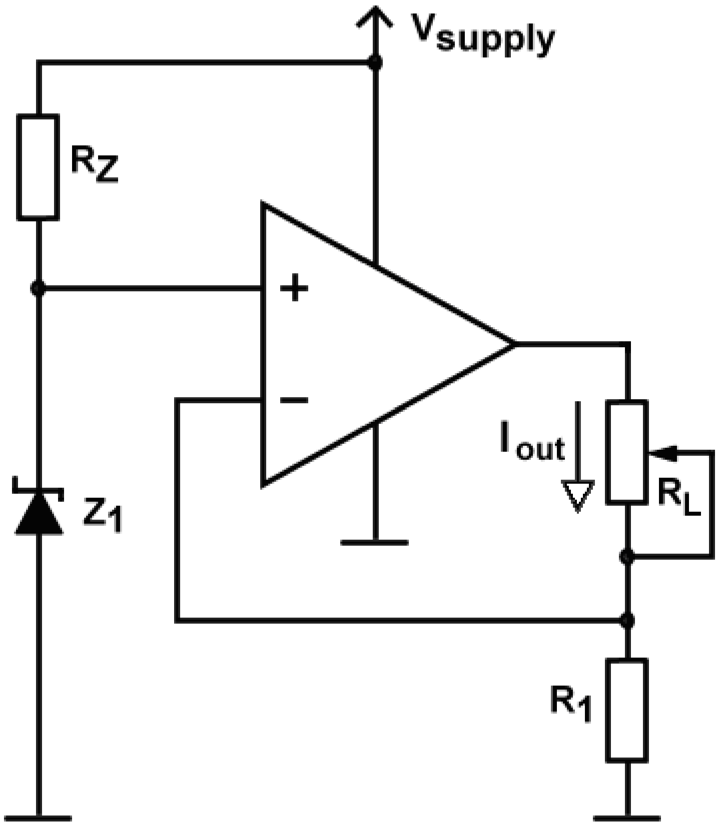


Figure 4. current generator with floating load

Parameters: V_{supply}=10V ; R_Z=1k ; R_1=3k ; R_L=10k potmeter ; Z_1=ZPD5.1

Homework:

4.1
Calculate the generated current (I_{out}) (at R_L=0). Find R_{Lmax}.

Measurements:

4.2
Measure I_{out} at R_L=0 (in mA with 3 decimal digits). Compare this with the calculated value. (*You can repeat the calculation with the measured values of R_1 and V_Z.*)

4.3
Measure R_{Lmax} (define it at 90% of I_{out}). Compare with the calculated value.

4.4 Find the output resistance (in the interval before reaching R_{Lmax}, where I_{out} changes only slightly).

5) Grounded current generator

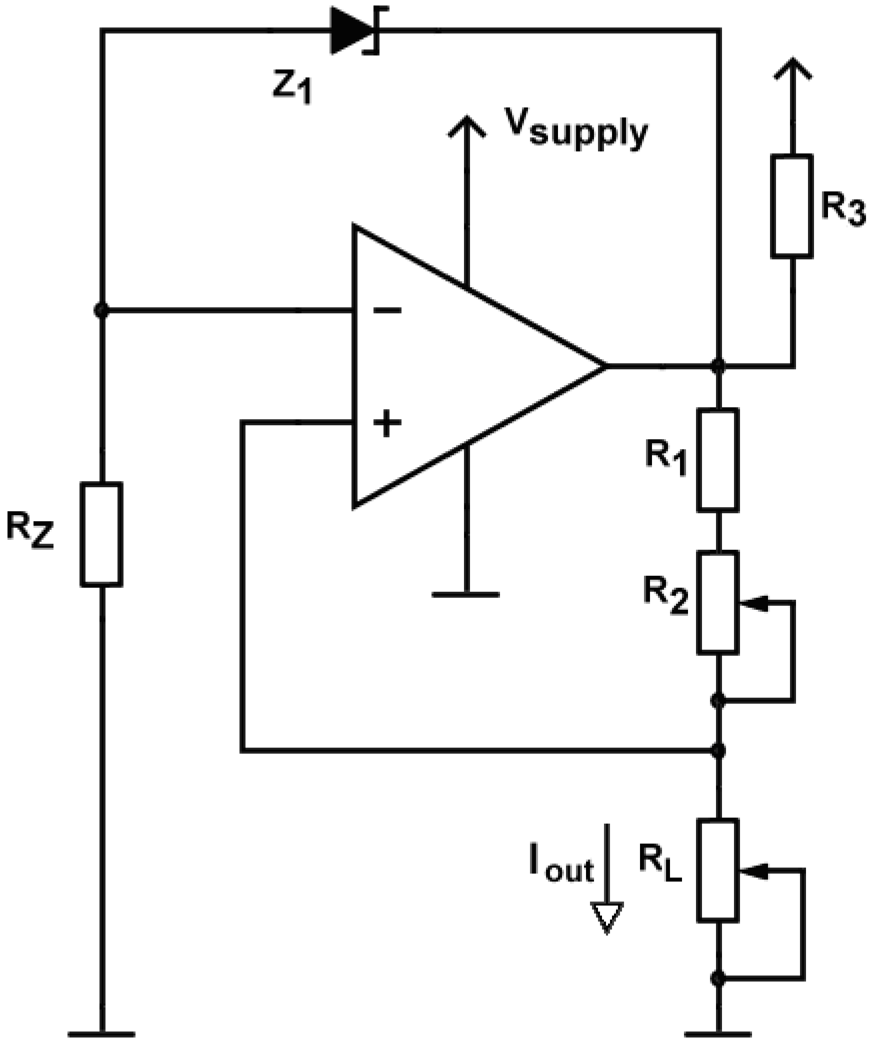


Figure 5.: Grounded current generator

Parameters: Z_1: LM285-2.5V precision voltage reference (band-gap reference) IC; R_Z=10kΩ ; R_1=20kΩ ; R_2=10kΩ potmeter ; R_3=100kΩ ; R_L=1kΩ potmeter ; V_{supply}=5V

This is similar to the previous circuit, but here one side of the load is connected to the zero potential. This makes is easier to measure the load's voltage (eg. if it's a sensor). This is also called a "precision current generator".

In this circuit R_3 is needed to provide a proper „starting potential” for the opamp. (At startup, all the potentials are at zero and thus the opamp's output may stay at zero and the zener/bandgap doesn't reach its breakdown voltage). R_1+R_2 resistors set up the generator current. (*A fixed resistor and a potmeter are used to provide for better precision in setting up the current than if using only a potmeter.)*

The circuit can be used as a voltage generator (similarly as the 2. and 3. circuits are practically the same), if we put a constant resistor in place of R_L and use the opamp’s output. We shall not measure that setup, as it wouldn’t provide that much new information for this lab.

Homework

5.1.
Calculate the generator current I_{out} (on R_L) if $(R_1+R_2)=25k\Omega$ and $V_Z=2.5V$.

5.2.
This circuit, in contrast with the other current generators discussed, can not be short-circuited, that is, there is a minimum load resistance. Explain why! Estimate R_{Lmin} if we know that the minimal current of the reference Z_1 is approximately 10µA!

5.3.
Calculate R_{Lmax} at $V_{supply}=5V$ and at $V_{supply}=10V$.

Measurements

5.4.
Build the circuit according to figure Figure 5. Let R_L load be first a 1kΩ potmeter. Setup 100µA current at $R_L=1k$, using R_2 potmeter. Observe the precision with which you are able to setup this current.

5.5
Measure R_{Lmin}. In this circuit we can try a different limit than previously (ie. allowing a smaller decrease of the current, to be more precise). Decrease R_L from 1k until the current decreases to about 98%. (At this point, take out the potmeter and measure R_{Lmin}.) If you use the ampermeter of the Hameg multimeter, it is suggested to use measurement range L3 (as in L2 the internal resistance is 100Ω, in L1 1000Ω, these are in series with R_L and thus can falsify the measurement – in L3 it's only about 10Ω). Another method is to measure the voltage of the fixed R_1 which is proportional to the current (the internal resistance of the voltmeter is large enough not to falsify this measurement). Compare the results with the calculations.

5.6 Find the output resistance (in the range between R_{Lmin} and R_{Lmax}). This tells us how precise the generator is.

5.7.
Voluntary exercise: Measure R_{Lmax}. To do this, use a 10kΩ resistor in series with a 10kΩ potmeter as load. Use a limit of about 98%. Compare the result with the calculations!

6) Transistorised current generator

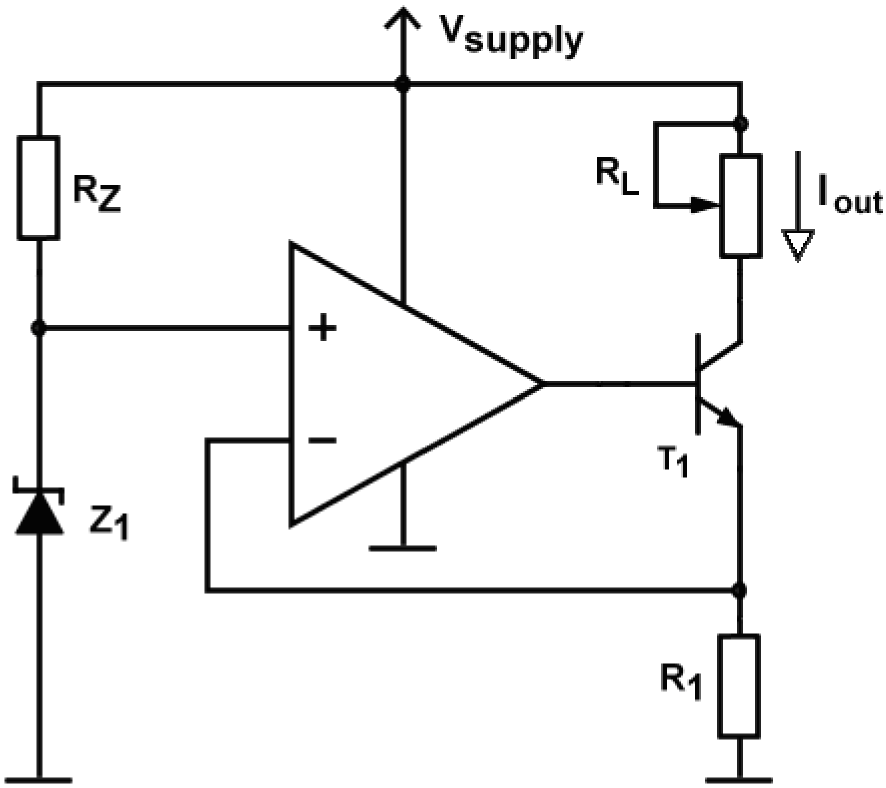


Figure 6.: Current generator with increased load current

Parameters: V_{supply}=15V ; Z_1=ZPD5.1 ; R_Z=3k ; R_1=1k ; T_1=BC301 ; R_L=1k potmeter

Using the external transistor, we can have higher load currents than what the opamp could output.

Homework:

6.1
Calculate the operating point values (V_Z, V_B, V_E, I_C, I_Z)!
Find R_{Lmax}!

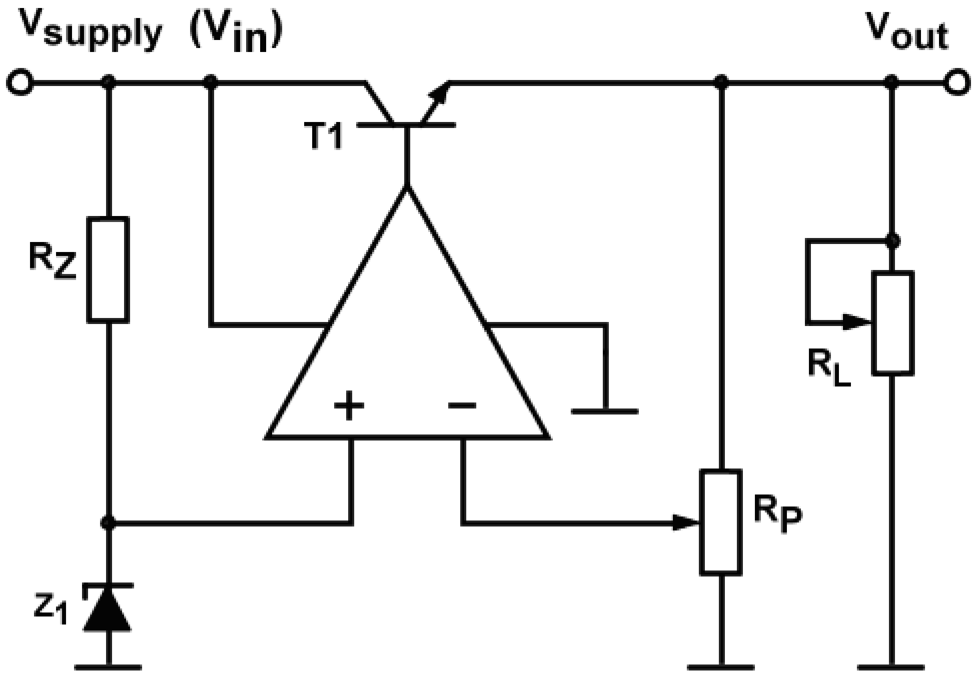
Measurements:

6.2
Measure the parameters from 6.1 and compare with the calculated values!

6.3
Measure the output resistance!

6.4
Voluntary exercise: By decreasing R_1 you can see that the circuit can output much larger current than the current limit of the opamp. (Don't exceed the max current of the transistor!) In this case you have to increase the current limit of the power supply unit.

7) Linear dissipative voltage regulator



7. ábra: Simple series pass transistor voltage regulator

Parameters: V_{supply}= V_{in} = 0..20V ; Z_1=ZPD5.1 ; R_Z=1k ; T_1=BC301 ; R_P=10k potmeter ; R_L=1k potmeter

This a simplified version of those circuits which we find inside dissipative (also known as linear, analog or series pass transistor) voltage regulator integrated circuits (such as LM7805, LM317 etc.). This circuit lacks the current and thermal limits, therefore make sure the current limit in the power supply unit is set up properly! Here the maximum current is limited by the transistor. Use **100mA** limit in this measurement.

Homework:

7.1
Let R_P' be the resistance of the potmeter between the slider and the zero potential.
Calculate the output voltage as a function of R_P' and V_{in} (let R_L be maximal) according to the following table.

	R_P'=3.3k	R_P'=5k	R_P'=10k
V_{in}=7V			
V_{in}=10V			
V_{in}=20V			

Measurements:

7.2
Measure the output voltage as a function of R_P' and V_{in} according to the following table (R_L maximal).

	R_P'=3.3k (cc. 1/3 of max)	R_P'=5k (cc. ½ of max)	R_P'=10k (max)
V_{in}=7V			
V_{in}=10V			
V_{in}=20V			

7.3
Calculate the dissipated power of the transistor at V_{in}=10V and supply current of 100mA. Setup R_L such that the supply current is just under 100mA (so as not to activate the current limit). Examine whether the operational point parameters change in time because of the self-heating. *Measure the currents and voltages right after setting up the above parameters, then wait some time (until you can feel the transistor heating up) and measure again.*

7.4
Voluntary exercise: find the output resistance of the circuit.(Measure V_{out0} at open circuit, then find $V_{out}=V_{out0}/2$ by using the potmeter as load.)