Electronics II. laboratory

Symmetric difference amplifier

2022.4.21.

Aims:

Analysis and parameter measurement of symmetric difference amplifier made of bipolar transistors.

The *italic text* in this guide usually represents hints and voluntary measurements. (You know, the stuff that makes up the exam questions.)

Component list

- 1 × MD2369 transistor pair (in common package, on a PCB)
- 1 × BC337 transistor
- 1 × ZPD3.3 Zener diode
- 1 × symmetrising (balun) transformer
- 2 × 100kΩ
- 3 × 10kΩ
- 2 × 2kΩ
- 1 × 1kΩ trimmer potentiometer

I. Theoretical background

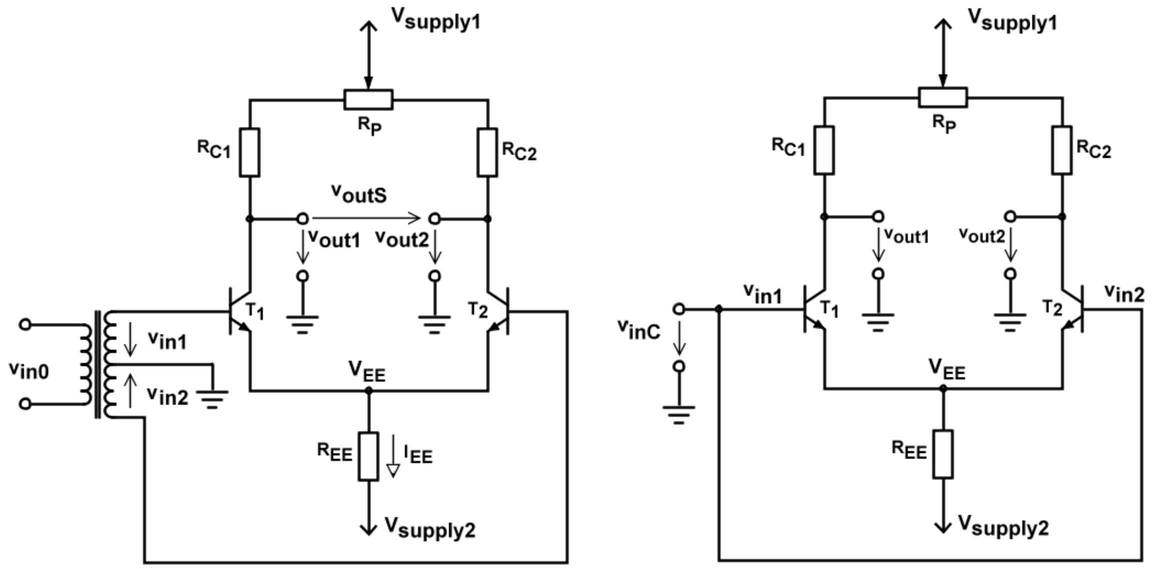


Figure 1. left: symmetric input, right: common mode input

In this measurement we analyse a symmetrical (two output) difference amplifier. Difference amplifiers can be analysed by two types of probe signals: symmetric and common mode signals. The responses to these will allow to find the response for arbitrary inputs, as long as the amplifier can be considered relatively linear (method of superposition).

The basic circuitry, most often analysed in books, is DC-coupled. That means, the bases of the transistors are connected to ground (for their operating point) through the input generator. If, in practice, we need AC coupling (such as connecting through capacitors), we need an extra resistor towards ground to provide the operating point voltages.

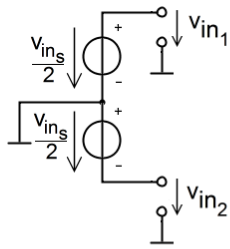
In this measurement, the symmetric inputs are created with the help of a center tap transformer. Thus the input is pure AC in this mode, and the center tap provides the ground for the operating point. In common mode, the function generator will provide the operating point (therefore make sure to have no DC offset turned on in the generator).

Symmetric input:

In this mode the two input signals are equal but of opposite sign:

$$v_{in1} = -v_{in2}$$

We can treat these as if generated by a double AC source of $\pm v_{inS}/2$:



$$v_{in1} = \frac{v_{inS}}{2}$$

$$v_{in2} = -\frac{v_{inS}}{2}$$

$$v_{inS} = v_{in1} - v_{in2}$$

v_{inS} is called the symmetric or differential input voltage.

This circuit has two outputs as well and we can define a differential output voltage:

$$v_{outS} = v_{out1} - v_{out2}$$

We can define gains for the different input-output combinations: between one input and one output, or between differential input and output (or even mixed). [1]

The definition (also used for measurement calculation) for symmetric or differential gain:

$$A_{VSS} = \frac{v_{outS}}{v_{inS}} = \frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}}$$

If the circuit is symmetrical (R_{C1}=R_{C2}, the potmeter is at half setting, the characteristics and temperature of the two transistors are identical), then the gain of the two sides are equal and thus if the inputs are equal in absolute value, the outputs will be as well.

$$\frac{v_{out1}}{v_{in1}} = \frac{v_{out2}}{v_{in2}} = \frac{v_{out1} - v_{out2}}{v_{in1} - v_{in2}}$$

Calculating gain:

The bases are at zero potential and the emitters are connected, thus the two BE junctions are in parallel and have the same voltage. Therefore, if characteristics are identical, the two DC emitter (and the two collector) currents will be equal as well. The common emitter point will be at approx. $V_{EE} = -0.7V$ potential.

If the (AC) input signals are symmetric, the AC components of the emitter currents will equal but opposite signed, and therefore cancel each other out on R_{EE}. Thus the emitter potential in AC is zero (v_{EE}=0), there is only DC current flowing on this resistor.

In this case the model for the two sides will be the classical Common Emitter Amplifier. The trick is that now emitter is at zero potential (in AC) without the need for the CE capacitor. (Because this way we can have different operation in symmetric and common mode, see later.) The gains for the two sides are therefore (without load):

$$A_{V1} = \frac{v_{out1}}{v_{in1}} = -g_{21(1)} R_{C1}$$

$$A_{V2} = \frac{v_{out2}}{v_{in2}} = -g_{21(2)} R_{C2}$$

in ideal case: $A_{V1} = A_{V2} = A_{VSS}$

To find out the transconductance g_{21}, again treat the transistors as having identical characteristics and thus having equal DC collector currents.

[1] In the symbols in this guide, the first index refers to the output, the second to the input. Eg. A_{VSC} is about how much a common mode input signal changes the symmetric (differential) output. Also, uppercase letters indicate constant or DC values while lowercase letters indicate time-variant or AC values usually. (In case of the inputs (not the supply) a DC signal is also treated as AC, because it can and will change.)

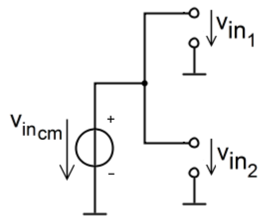
$$I_{EE} = \frac{V_{EE} - V_{supply2}}{R_{EE}}$$

in ideal case: $I_{C1} = I_{C2} = \frac{I_{EE}}{2}$

$$g_{21} = \frac{I_C}{V_T} = \frac{I_{EE}}{2V_T} = \frac{V_{EE} - V_{supply2}}{2R_{EE}V_T}$$

Common mode input:

In this case the two inputs are equal:



$$v_{in1} = v_{in2} = v_{inCM}$$

The arithmetic average of the outputs is called the common mode output:

$$v_{outC} = \frac{v_{out1} + v_{out2}}{2}$$

(See also section "Arbitrary input")

The common mode gain:

$$A_{VCC} = \frac{v_{outC}}{v_{inC}} = \frac{\frac{v_{out1} + v_{out2}}{2}}{v_{inC}}$$

In ideal case, if $v_{in1} = v_{in2} = v_{inC}$, then $v_{out1} = v_{out2} = v_{outC}$ and thus

$$A_{VCC} = \frac{v_{outC}}{v_{inC}} = \frac{v_{out1}}{v_{in1}} = \frac{v_{out2}}{v_{in2}}$$

In ideal case in common mode the outputs are equal and thus the differential output ($v_{out1} - v_{out2}$) is zero.

Calculating common mode gain:

In this case the two AC emitter currents are equal and their sum is therefore not zero, thus the common emitter current i_{EE} is not zero and v_{EE} is not zero. The emitter resistor therefore doesn't disappear in the AC model now, so we have to remember the "Common Emitter Amplifier with negative feedback in the emitter" topic from previous studies.

We can substitute R_{EE} with two parallel resistors each of value $2R_{EE}$. Using the approximate formula for this amplifier (unloaded case):

$$\frac{v_{out1}}{v_{in1}} = -\frac{R_{C1}}{2R_{EE}}, \quad \frac{v_{out2}}{v_{in2}} = -\frac{R_{C2}}{2R_{EE}}$$

in ideal case: $A_{VCC} = \frac{v_{outC}}{v_{inC}} = -\frac{R_C}{2R_{EE}}$

Arbitrary input:

If the two inputs are arbitrary signals, we can treat them as made up of two components: symmetric and common mode. Then we can use the method of superposition - analyse the behaviour of the circuit for both cases, then add the partial results. (*Remember: method of superposition is applicable for linear networks only. Here we use the small signal approximation, where we treat the nonlinearity of the transistor characteristics as small enough, if the input signal is very small.*)

The two components will be:

$$v_{inS} = v_{in1} - v_{in2}$$

$$v_{inC} = \frac{v_{in1} + v_{in2}}{2}$$

From these the original input signals can be composed:

$$v_{in1} = v_{inC} + \frac{v_{inS}}{2}$$

$$v_{in1} = v_{inC} - \frac{v_{inS}}{2}$$

The output signals can be decomposed in a similar way if needed.

We have already seen that the gain is very different in symmetric and common modes. That is exactly the purpose: to amplify symmetric components while suppress common mode components.

In both analogue and digital technics we can find the method of symmetrical transfer using three wires in order to decrease the effects of external interference (eg. USB, CAN, RS-485 digital communications or in audio recording studios). One wire is the zero (ground), the other two carry the signal in symmetric form (normal and inverted signal). At the destination, the received signal is measured between the two signal wires. If the two signal wires are physically very close to each other, and the source of radiated (EM) interference (noise) is relatively far away, then we can assume that both signal wires will receive approximately the same interference (in amplitude and phase). The useful signal is of opposite polarity on the two wires. At the end, we subtract the potentials of the two wires, thus the useful symmetrical signal is preserved (eg. 1−(−1)=2) but the interference signal is (almost) removed (1−1=0).

A difference amplifier can add amplification to this trick, by having high (>>1) gain for symmetric signals, and very low (<<1) gain for common mode signals (components). (Note: the common mode interference is suppressed even if the useful signal is not symmetric, but latter is recommended also to decrease the EM radiation of the wire which would induce interference for other devices.)

The difference amplifier has two basic forms. One of them has two outputs (symmetric or differential output), the other has only one output (asymmetric). In this measurement we use the symmetric circuit. Symmetric version can be useful for example if we want to transmit our symmetric signal over a long distance and need an amplifier at the beginning or in the middle of the line. In the asymmetric circuit, we use only the first output, thus R_{C2} can be replaced by a short circuit. This version can be used at the end of a line, for example if we need one point of the load to be grounded. Difference amplifiers (in a somewhat more complicated, but recognizable form) are the input stages of operational amplifiers. Most opamps are built with one (asymmetric) output and thus contain the asymmetric difference amplifier inside, but symmetrical ones also exist. These circuits can be built from bipolar transistors, JFETs and MOSFETs or even from a combination of these.

In *circuits with symmetrical output* the aim is to have no traces of a common mode input component in the differential output ($v_{out1}-v_{out2}$). This can be quantified by the parameter A_{VSC}:

$$A_{VSC} = \frac{v_{outS}}{v_{inC}} = \frac{v_{out1} - v_{out2}}{v_{inC}}, \text{ if } v_{in1} = v_{in2} = v_{inC}$$

or in a more general case

$$A_{VSC} = \frac{v_{outS}}{v_{inC}} = \frac{v_{out1} - v_{out2}}{\frac{v_{in1} + v_{in2}}{2}}$$

In ideal case this parameter is zero for the symmetric output amplifier, as the two outputs are equal in common mode. If the two collector resistors are not equal:

$$A_{VSC} = \frac{v_{out1} - v_{out2}}{v_{inC}} = \frac{v_{out1}}{v_{inC}} - \frac{v_{out2}}{v_{inC}} = -\frac{R_{C1}}{2R_{EE}} - \left(-\frac{R_{C2}}{2R_{EE}}\right) = \frac{R_{C2} - R_{C1}}{2R_{EE}}$$

which is not zero, but still very small (as $R_{C2}-R_{C1}$ is normally very small and R_{EE} is large). Transistor parameter differences can also cause non-zero result.

Commom mode rejection ratio (CMRR) tells the ratio of the symmetric and common mode gains.

In symmetric output:

$$CMRR = \frac{A_{VSS}}{A_{VSC}}$$

$$CMRR[dB] = \left(20 \cdot \lg \frac{A_{VSS}}{A_{VSC}}\right)[dB] = a_{VSS}[dB] - a_{VSC}[dB]$$

For the *asymmetric output circuit*, differential output can't be defined. As the output is on one side only, the effect of a common mode signal will always be shown on the output, mixed with the output from the symmetric (useful) signal (after which it can't be removed).

Therefore we need to modify our definition for this circuit:

$$A'_{VSC} = \frac{v_{out1}}{v_{inC}} = \frac{v_{out2}}{v_{inC}} = -\frac{R_{C1}}{2R_{EE}} \text{ (which is thus equal to } A_{VCC}\text{)}$$

(Though in this case calling it A_{VSC} is probably not a good idea as the output is not symmetrical any more.)

The CMRR in this case will have $A_{VSS}/2$ (because of the one-sided output) divided by A_{VSC}'.

$$CMRR_{asymmetric} = \frac{A_{VSS}^{'}}{A_{VSC}^{'}}$$

where

$$A_{VSS}^{'} = \frac{v_{out1}}{v_{inS}} = \frac{A_{VSS}}{2}, \text{ if } v_{in1} = -v_{in2}$$

$$A_{VSC}^{'} = \frac{v_{out1}}{v_{inC}} = \frac{v_{out1}}{v_{in1}}, \text{ if } v_{in1} = v_{in2} = v_{inC}$$

In both circuits, but especially with the asymmetric, the CMRR can be increased by increasing R_{EE}. This, however, results in decreasing I_C and g_{21} which decreases AVSS.

This problem can be solved by putting a current generator instead of R_{EE}, thus combining higher current with higher resistance. In this case the resistance will be the dynamic output resistance of the current generator (which is known to be very large without decreasing the current). In opamps, a so-called current mirror circuit is used for this. Here we shall use the previously studied circuit with one transistor and Z-diode. This works so well that the common mode output can become too small to be measureable in our lab (and we'll only see noise on the scope).

II. Calculations (homework, before coming to laboratory!)

1) Symmetric input (Figure 2):
   - Calculate the operating point (DC) voltages and currents of the circuit on in ideal case. (R_P setup 50-50%, R_{C1}=R_{C2}, transistor parameters equal).
   - Calculate the output offset voltage ($V_{C1}-V_{C2}$), if R_{C1} is 5% greater than the nominal value and $I_{C1}=1.1 \cdot I_{C2}$.
   - Calculate the symmetrical (differential) voltage gain in ideal case.

2) Common mode input (Figure 3):
   - Calculate the common mode voltage gain in ideal case.
   - Calculate the differential voltage gain when using common mode input, in ideal case (that is, how much of the input CM signal transfers to a symmetric output).
   - Calculate the previous two gains (A_{VCC} and A_{VSC}) if R_{C1}=10.1kΩ.
   - Calculate the Common Mode Rejection Ratio (CMRR) for ideal and non-ideal (ie. exercise 6.) for symmetric (differential) output.
   - Calculate the CMRR if only one output (v_{out1}) is used (that is, we have an asymmetric output) (*In practice in such applications R_{C2} is replaced by a shortcircuit. Because we only have one output, only one index will be used for the gains, which will refer to the input.*)

3) Calculate the DC emitter current for Figure 4. Parameters: R_{E3}=2kΩ ; R_{B3}=2kΩ ; Z_1: ZPD3.3, $V_{supply1}$ = +12V ; $V_{supply2}$ = −12V

Exercises

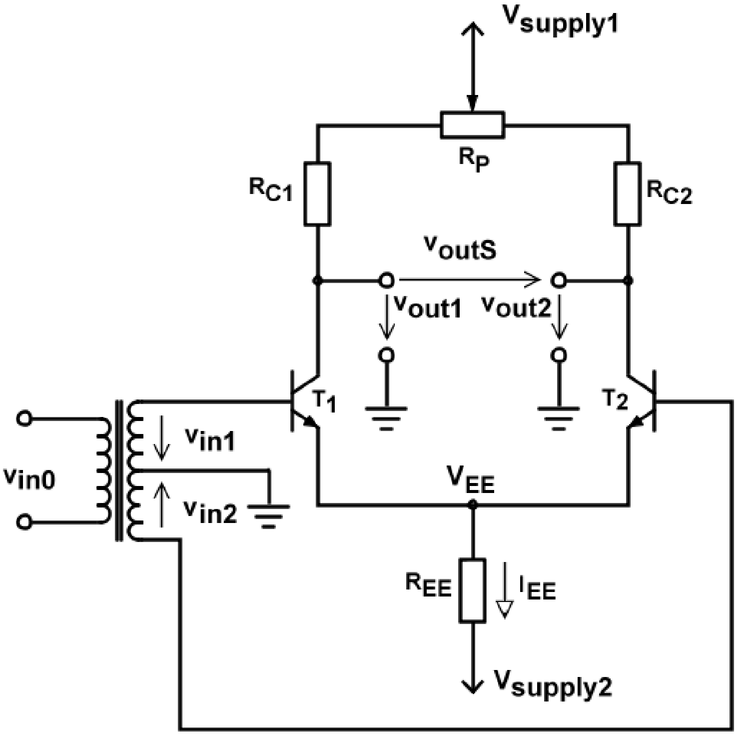


Figure 2.: symmetric input

Parameters:
$R_{C1}=R_{C2}=10k\Omega$; $R_{EE}=10k\Omega$; $R_P=1k\Omega$ trimmer ; $V_{supply1} = +12V$; $V_{supply2} = -12V$
Before starting the measurement, set up 20mA current limit on both power supply outputs!

II. Measurements

1. Symmetric signal

Before building the circuit: Use the function generator to apply such a sinusoidal signal to the primary winding of the transformer so that the signal and the secondary windings has parameters f=5kHz, V_p=100mV. Examine the two secondary signals on the oscilloscope, make notes of the signals with correct phases and amplitudes. (The secondary coils should have equal number of windings. The symmetry of the two signals can be proven by using the ADD function of the scope (find it in Math menu for the digital scopes), the sum of the two should be zero).

2. Operating point and output offset

Build the circuit from Figure 2. Don't connect the function generator to the transformer yet.
The DC voltage between V_{out1} and V_{out2} is the output offset voltage. Change the value of R_P potentiometer until the offset voltage is minimal. Keep R_P in this position for the rest of the measurement. Write down the minimal value for the offset.
Measure the operating point (DC) parameters: V_{EE}, V_{C1}, V_{C2}. Using these values and R values, calculate the I_{EE}, I_{C1} and I_{C2} currents. Compare with the homework calculations.

3. Symmetrical voltage gain

Use the function generator to apply such a sinusoidal signal to the primary winding of the transformer so that the signal and the secondary windings has parameters f=5kHz, V_{eff}=20mV. (Measure effective value (RMS) using the AC mode of the multimeter.)

Using an oscilloscope check if the output signals (v_{out1} and v_{out2}) are distorted. If they are, decrease the input voltage amplitude. (Note: always check that the output signal is not distorted even if the guide doesn't ask to do it.)

Examine and draw the time functions of v_{in1} – v_{out1} ; v_{in2} – v_{out2} signal pairs, the v_{outS} – v_{inS} signal pair and the v_{EE} signal.

Find out A_{VSS} from the measured v_{outS} and v_{inS} peak-to-peak or RMS values. Compare it to the previously calculated value.

4. Common mode voltage gain

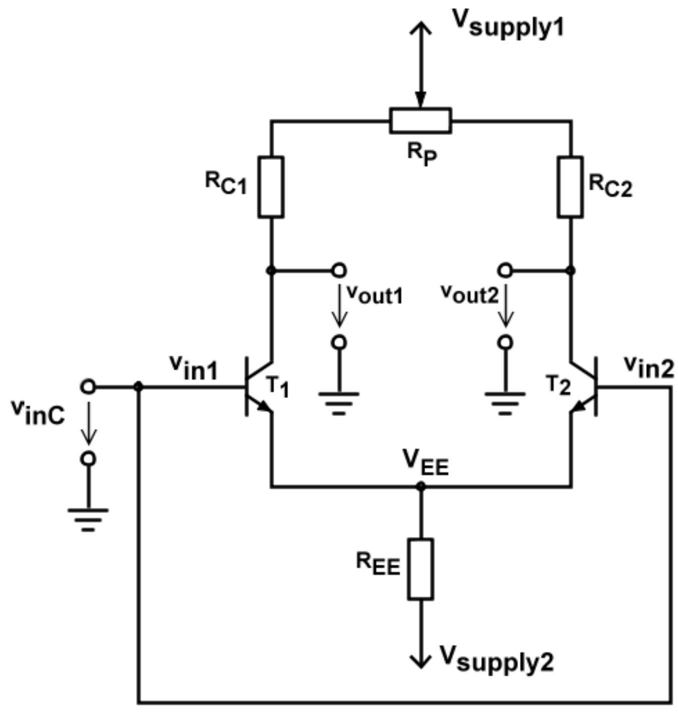


Figure 3.: common mode input

Here we don't need the transformer. Instead, connect the two inputs together to the function generator (Figure 3.). Use f=5kHz, V_p=2V sinewave.

Make sure the input signals are not distorted. Use an AC multimeter to measure the output signals v_{out1} and v_{out2}.

Extra: Compare the oscilloscope and the multimeter on the applicability of measuring these small signals.

Find out A_{VSC}. $A_{VSC} = \frac{v_{outS}}{v_{inC}} = \frac{v_{out1} - v_{out2}}{\frac{v_{in1} + v_{in2}}{2}}$, if $v_{in1} = v_{in2} = v_{inC}$

Find out the CMRR. Use the A_{VSS} from the previous exercise and A_{VSC} from this exercise.

Extra: Find out CMRR for the asymmetric (one sided) output as well. Use the v_{out1} values from this and the last exercise.

5. Symmetric amplifier with current generator

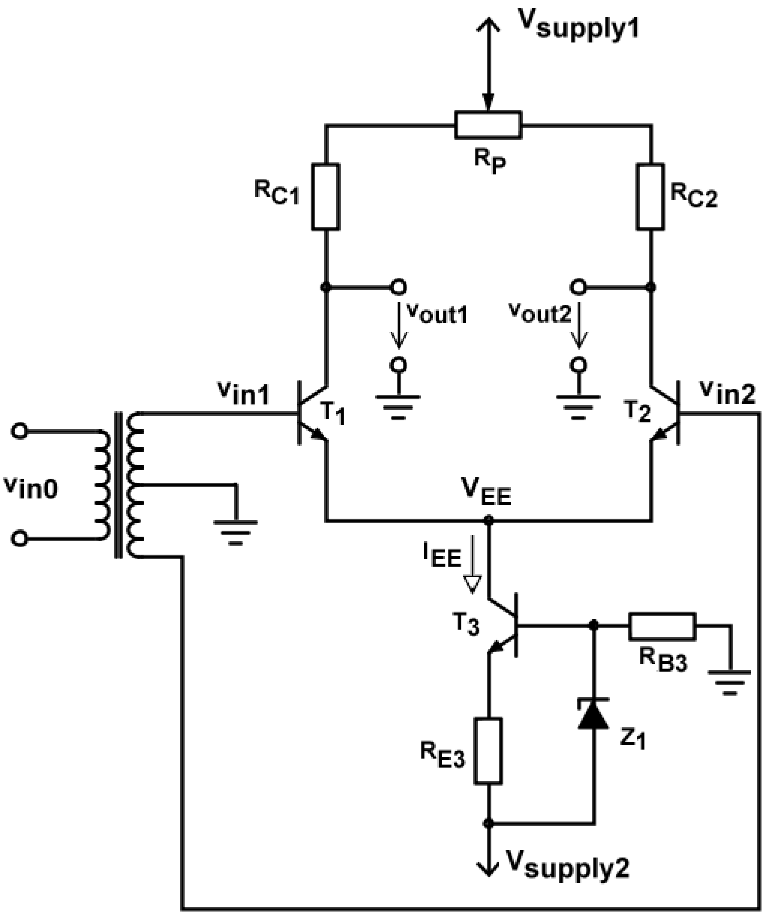


Figure 4.: symmetric amplifier with current generator

Build the circuit from figure 3! Parameters: same as previously, plus R_{E3}=2kΩ ; R_{B3}=2kΩ ; Z_1: ZPD3.3 ; $V_{supply1}$ = +12V ; $V_{supply2}$ = −12V

Do exercises 3 and 4 for this circuit, too! Compare the results with the previous results (ie. without the current generator) and analyse the difference.

(Find out the r_{EE} dynamic resistance of the current generator. This practically replaces R_{EE} in the AC calculations. Use the information from Electronics I. laboratory measurement 2, current generator output resistance. Use a common mode

DC input signal and measure V_{EE} and I_{EE} in at least two points. The dynamic resistance will be $r_{EE} = \frac{\Delta V_{EE}}{\Delta I_{EE}}$ *)*

Test questions

1) Describe the goal and method of differential signalling!
2) How to calculate symmetric and common mode components of an arbitrary signal?
3) Draw a symmetric difference amplifier circuit with transistors! Note the inputs and outputs.
4) Explain the operation of the diff.amp. with symmetric input!
5) Explain the operation of the diff.amp. with common mode input!
6) What is the CMRR for differential output?
7) What is the CMRR for asymmetric output?
8) What are the criteria for a large CMRR?
9) How do we increase CMRR?