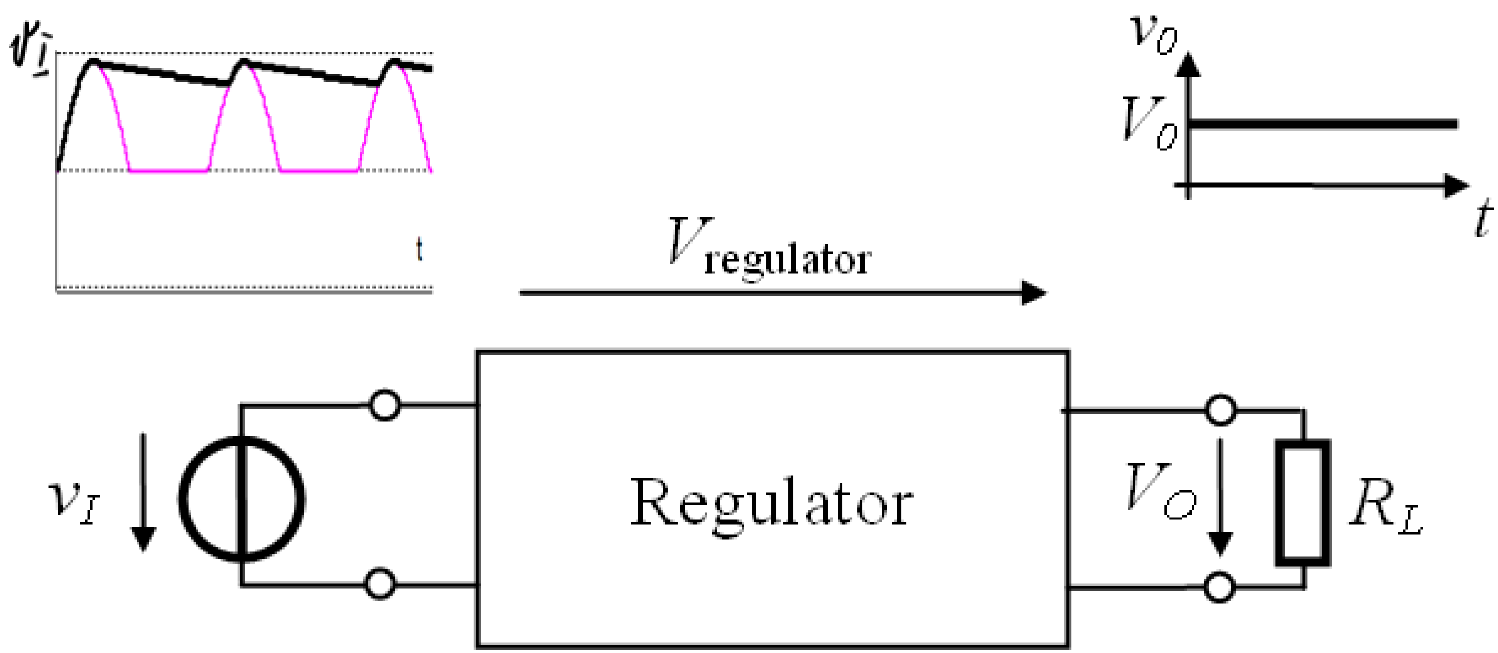
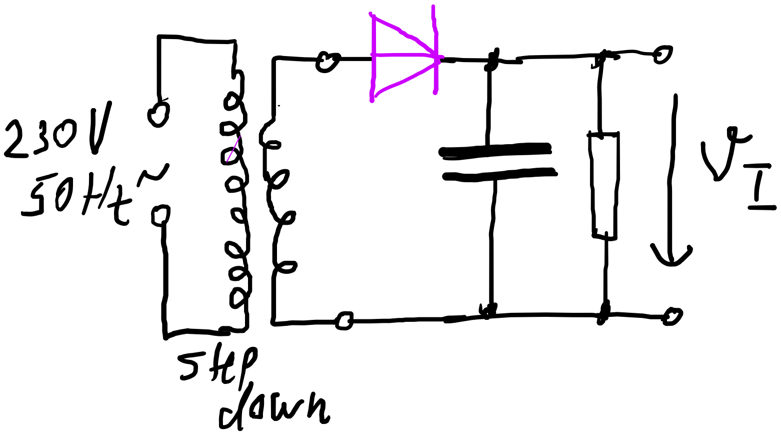
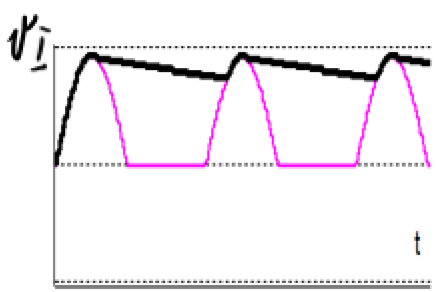
DC Voltage Regulators

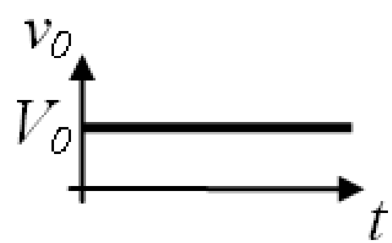
A **voltage regulator** is an electronic circuit which maintains the **output voltage (almost) constant** despite changes within some specified limits in the load current, input voltage, temperature, etc.

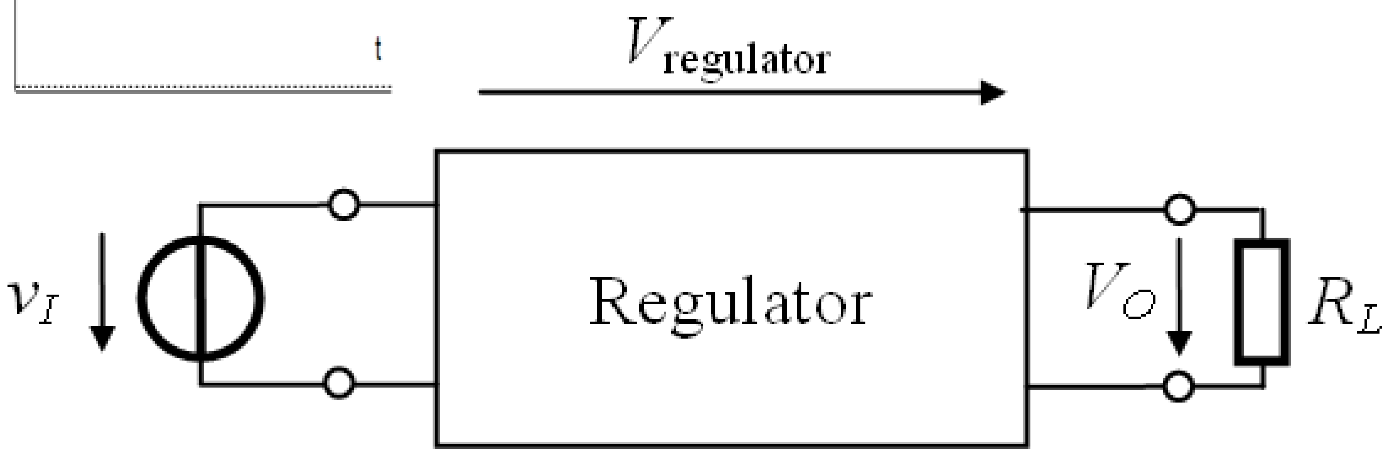


$$V_O = v_I - v_{regulator}$$









$$V_O = v_I - v_{regulator}$$

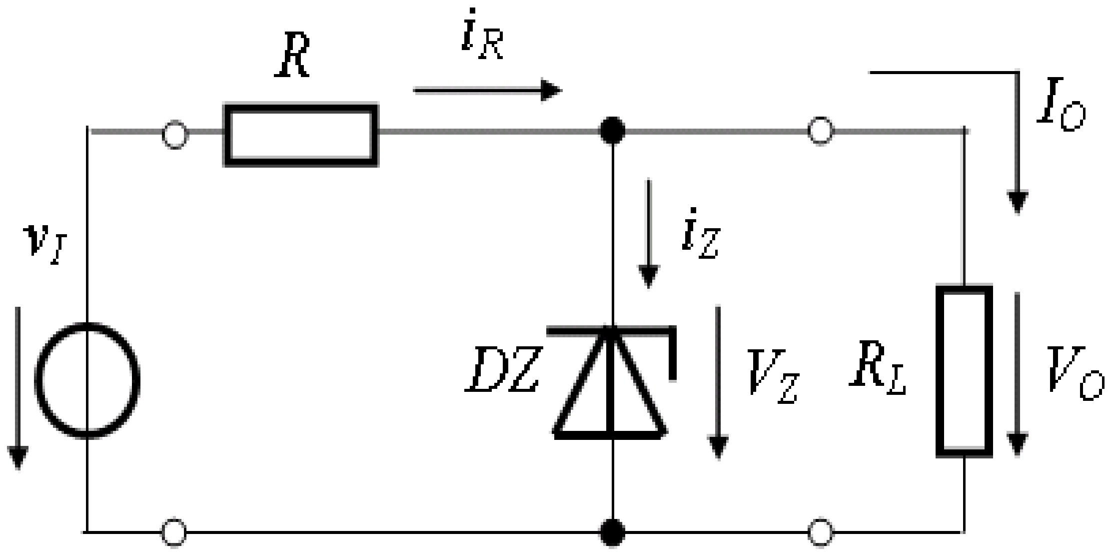
Regulator types

- **Parametric regulators** (with ZD, without active devices)

- **Linear voltage regulators** (contain active devices) – the transistors that adjust the output voltage to the default value operate in the linear regime (permanent conduction).

- **Switching voltage regulators** (contain active devices) – the main transistors that adjust the output voltage to the default value operate in switching regime, generally at a frequency $\geq$ 20KHz

Parametric voltage regulator



$$i_Z = i_R - I_O$$

$$i_R = \frac{v_I - V_Z}{R}$$

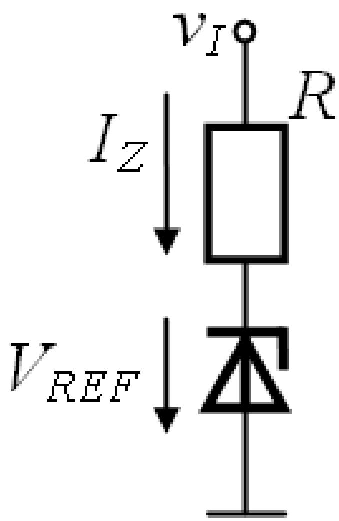
$$i_Z = \frac{v_I - V_Z}{R} - I_O$$

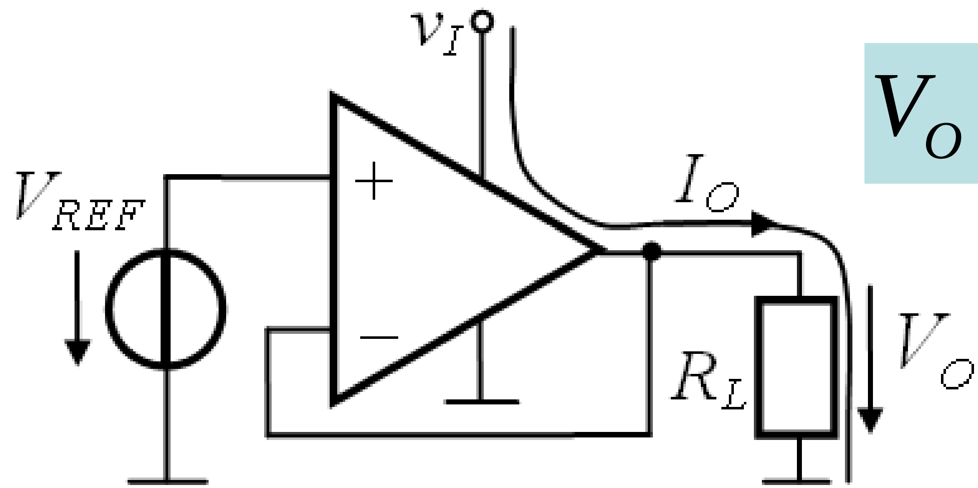
$$R = \frac{v_I - V_Z}{I_{Znom} + I_O}$$

Please revisit the Zener Diode paragraph!

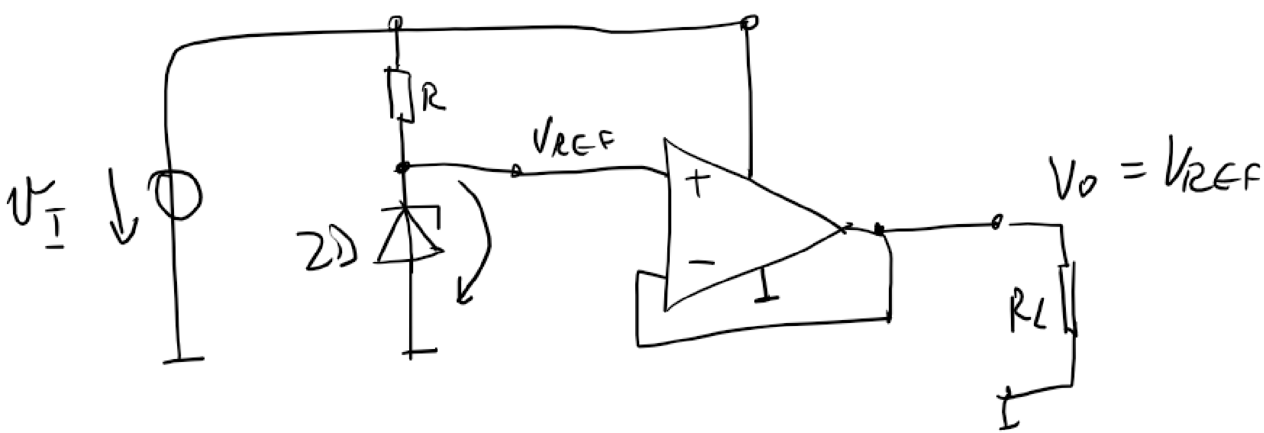
Op-amp voltage regulators

A **reference voltage** is always necessary in a voltage regulator



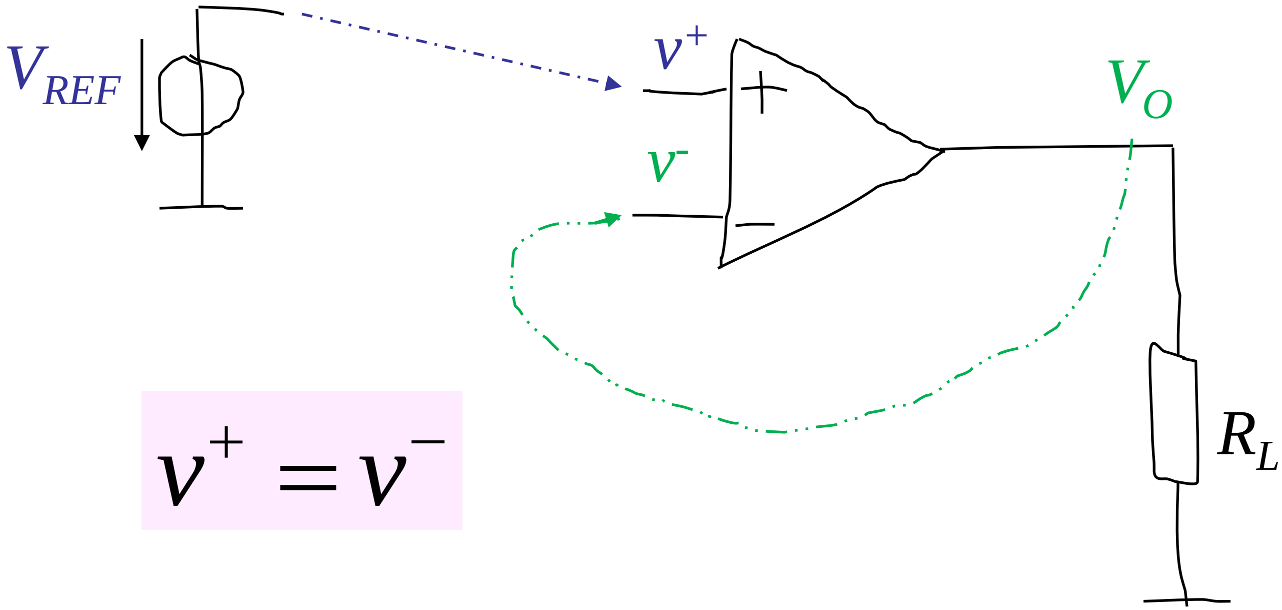


$$V_O = V_{REF}$$



Op-amp voltage regulator

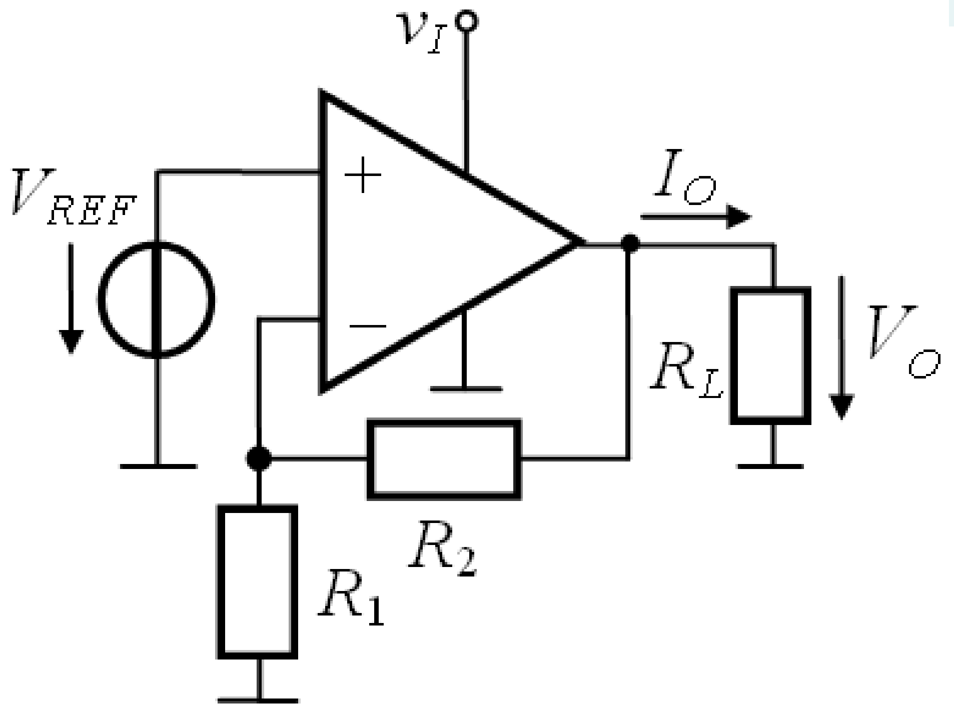
$$V_O \neq V_{REF}$$



$$v^+ = v^-$$

Op-amp voltage regulator – cont.

$$V_O > V_{REF}$$



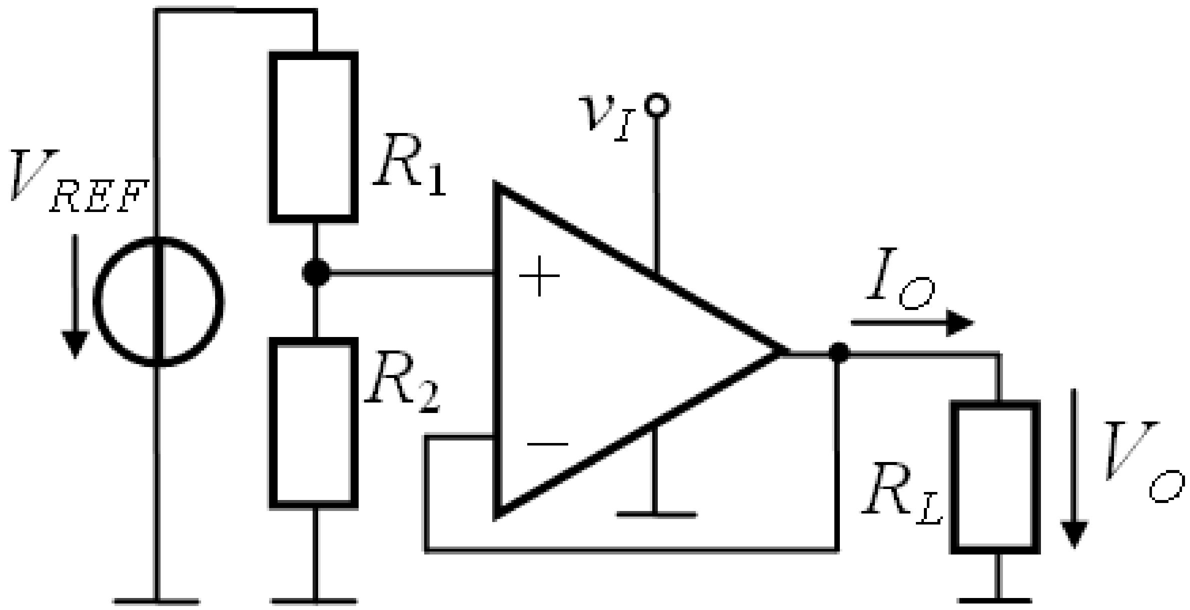
$V_O = ?$

$$V_O = \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

Op-amp voltage regulator – cont.

$$V_O < V_{REF}$$

Consider that V_{REF} is given

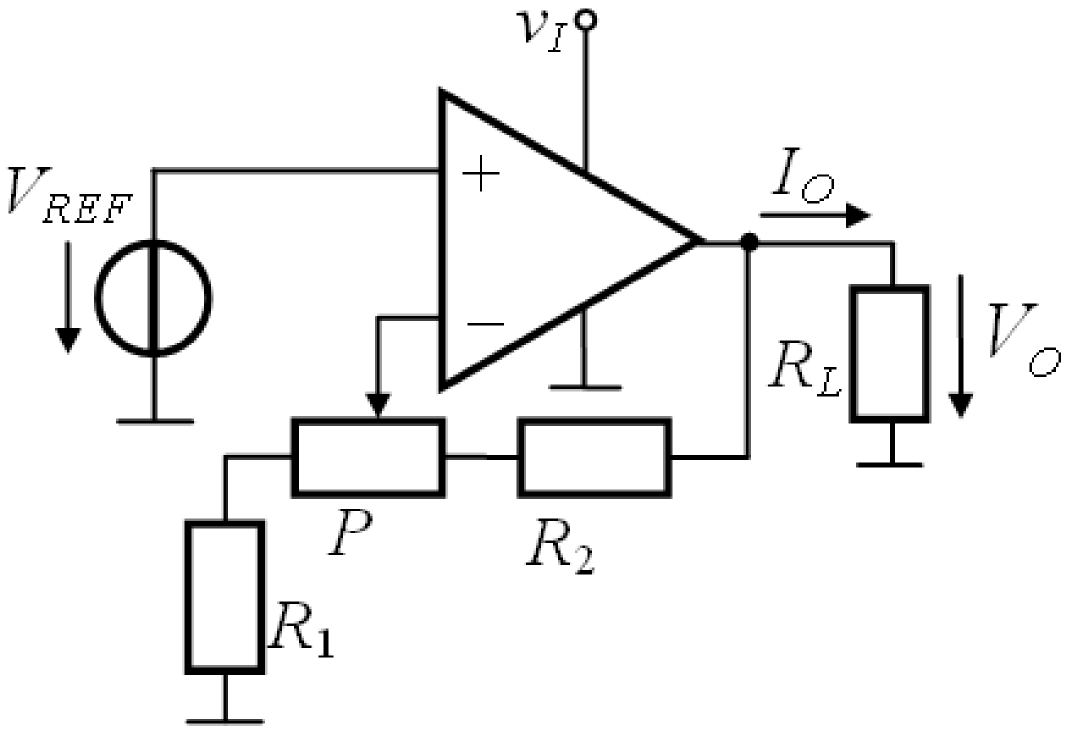


$V_O = ?$

$$V_O = \frac{R_2}{R_1 + R_2} V_{REF}$$

Op-amp voltage regulator – cont.

Adjustable V_O , $V_O > V_{REF}$



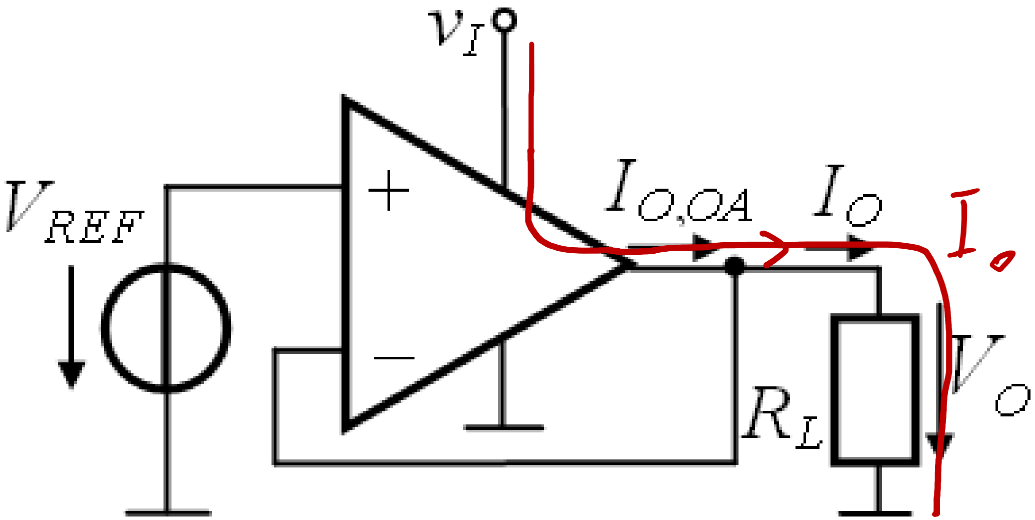
V_O=?

$$V_{O\min} = \left(1 + \frac{R_2}{P + R_1}\right) V_{REF}$$

$$V_{O\max} = \left(1 + \frac{R_2 + P}{R_1}\right) V_{REF}$$

- How does the circuit look like for adjustable V_O , $V_O < V_{REF}$ **?**
- How does the circuit look like for adjustable V_O
  $V_{Omin} < V_{REF}$ and $V_{Omax} > V_{REF}$ **?**

Increasing the output current



$$I_{O\max} = I_{O,OA\max}$$

For common use op amp:

$$I_{O,OA\max} \approx 20\text{mA}$$

$V_o = 10V$

$R_L = 1k\Omega$

$I_o = \frac{10V}{1k\Omega}$

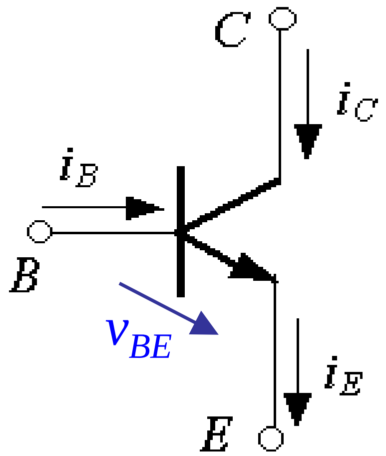
? Higher current in the load

Solutions:

- power op amp; e.g. TDA2030, up to 3.5A
- **current amplifier between op amp and load (transistor)**

BJT in active region (a_F)

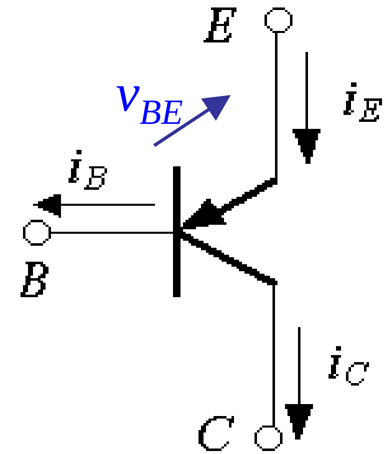
npn



$v_{BE} > 0.6\text{V},\ T-(a_F)$

$v_{BE} < 0.6\text{V},\ T-(off)$

pnp



$v_{BE} < -0.6\text{V},\ T-(a_F)$

$v_{BE} > -0.6\text{V},\ T-(off)$

$$i_E = i_C + i_B$$ Always valid

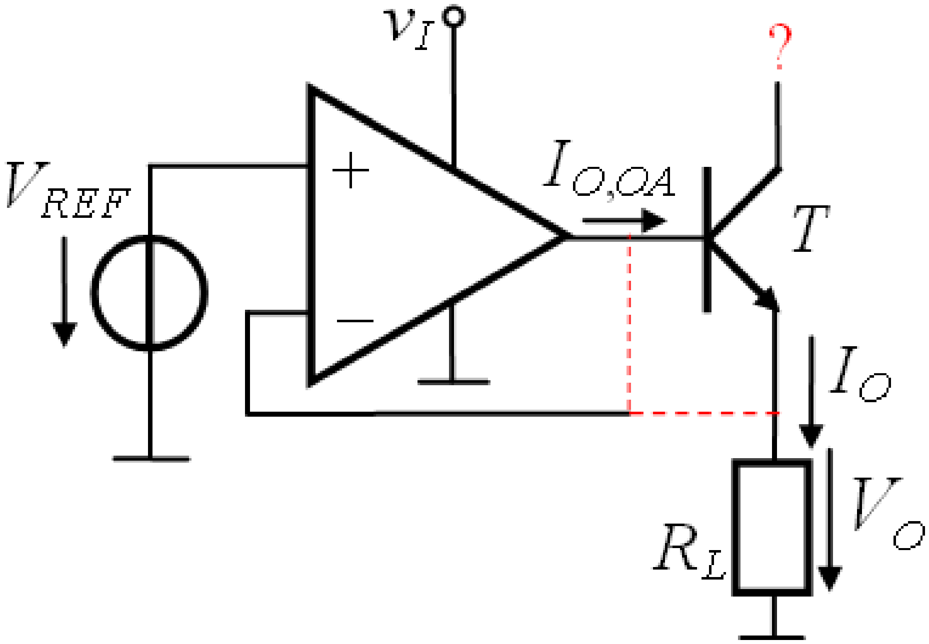
In the active region (a_F) $\boldsymbol{i_C = \beta i_B}$ $\beta \geq 100$ – as a rough guide

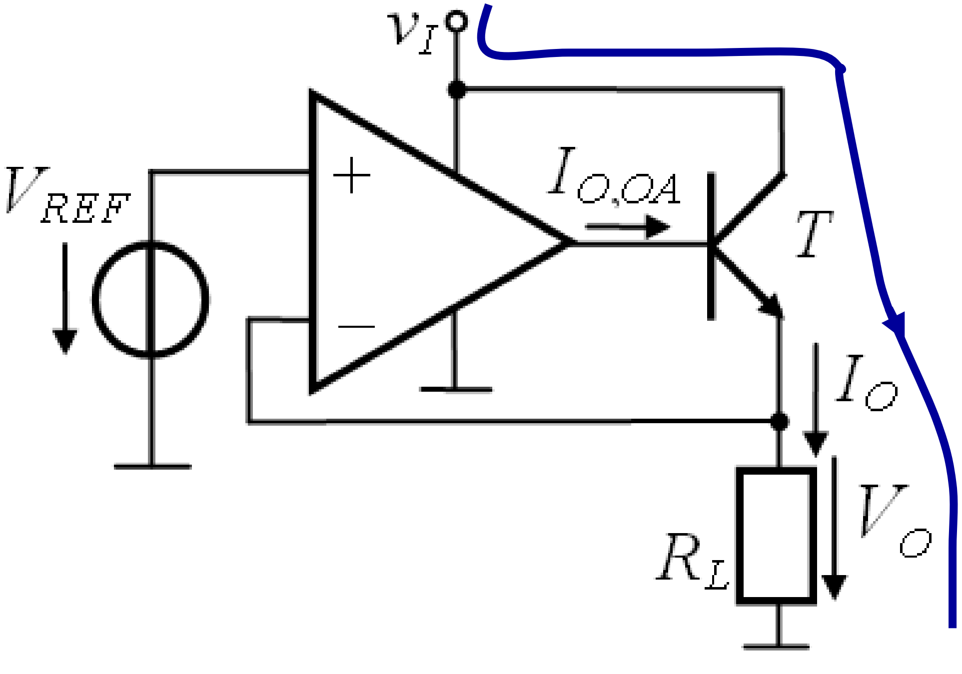
$$i_E = i_C + \frac{1}{\beta} i_C = i_C\left(1 + \frac{1}{\beta}\right) \approx i_C$$

$$i_E \approx i_C$$

$$i_E = (\beta+1) i_B \approx \beta i_B$$

$$i_E \approx i_C = \beta i_B$$

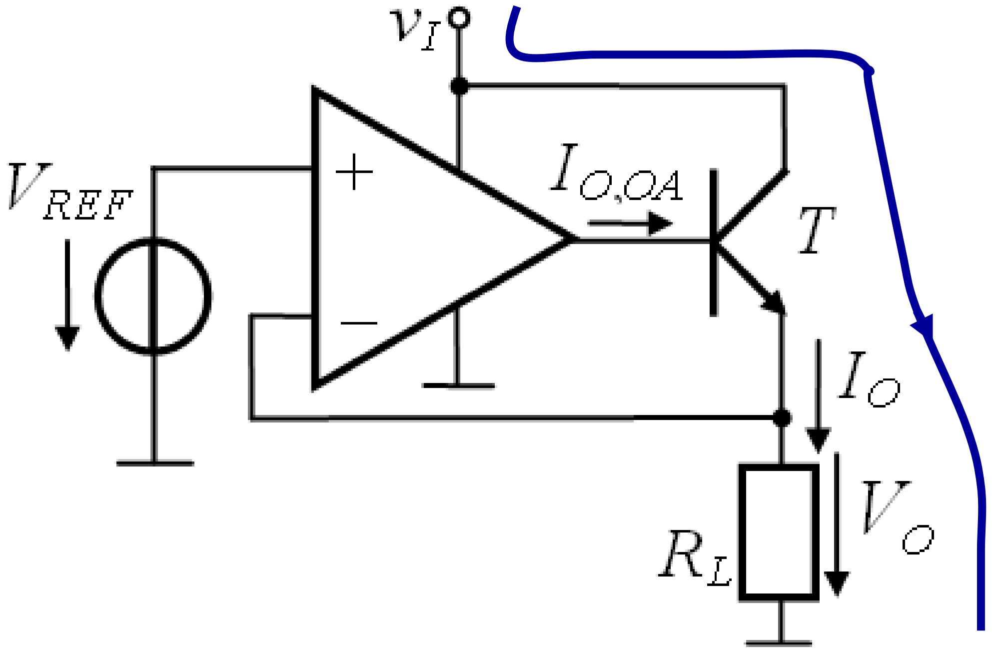




$$I_{O\max} = \beta I_{O,OA\max}$$

T – series pass transistor

$$V_O = V_{REF}$$



T – series pass transistor

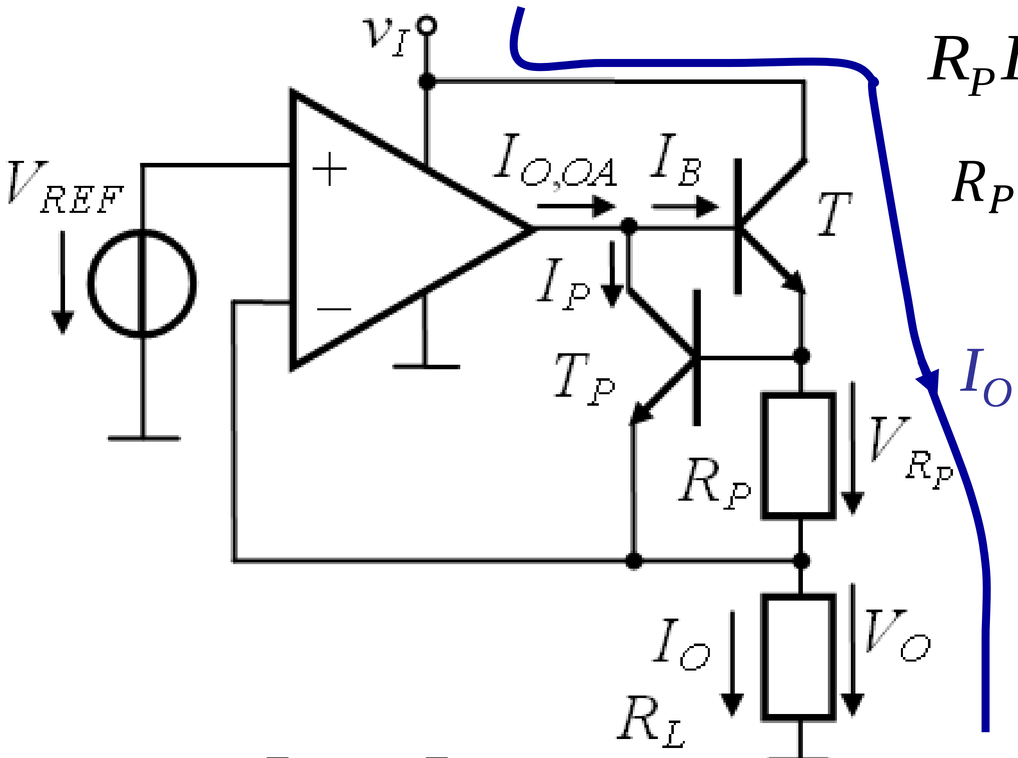
$$V_O = V_{REF}$$

The solution to use a BJT to increase the output current is applicable for all previous discussed voltage regulator configurations, without affecting the expression and value of the output voltage.

Overcurrent and shortcircuit protection

$R_L \to 0$ $\quad I_O \to \infty$ The current must be limited!

- oversee I_O
- when I_O exceeds a certain value, protection circuit triggers



$R_P I_O < 0.6\text{V}; \quad T_P - (off); \quad I_P = 0$

$R_P I_O > 0.6\text{V}; \quad T_P - (a_F); \quad I_P > 0$

$$I_{O\max} = \frac{V_{R_P}}{R_P} + I_P$$

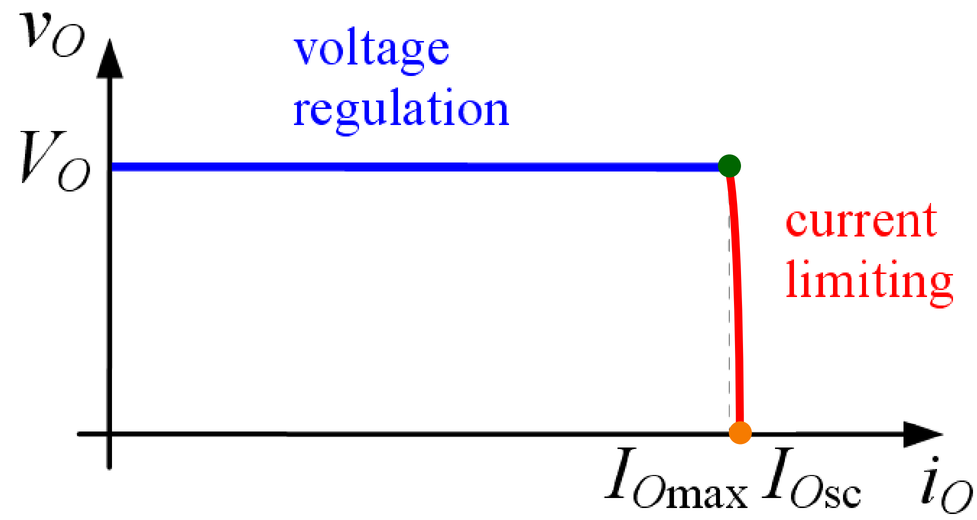
$$I_{Omax} = \frac{0.7\text{V}}{R_p} + I_p \approx \frac{0.7\text{V}}{R_p}$$

$$I_{Omax} \approx \frac{0.7\text{V}}{R_p}$$

When $I_O = I_{O\max}$

$R_L \downarrow, \underline{I_O \uparrow}, I_O R_P \uparrow, I_P \uparrow, I_B \downarrow, \underline{I_O \downarrow}$ $\qquad V_O \downarrow$

The output characteristic



- voltage regulation region

$$v_O = V_O, \quad I_O = \frac{V_O}{R_L}$$

- knee point

$$v_O = V_O, \qquad I_O = I_{O\max} = \frac{0.7\text{V}}{R_P}$$

- current limiting region

$$v_O < V_O, \ v_O = I_O R_L, \quad I_O = I_{Omax} + I_p \approx \frac{0.7\text{V}}{R_p}$$

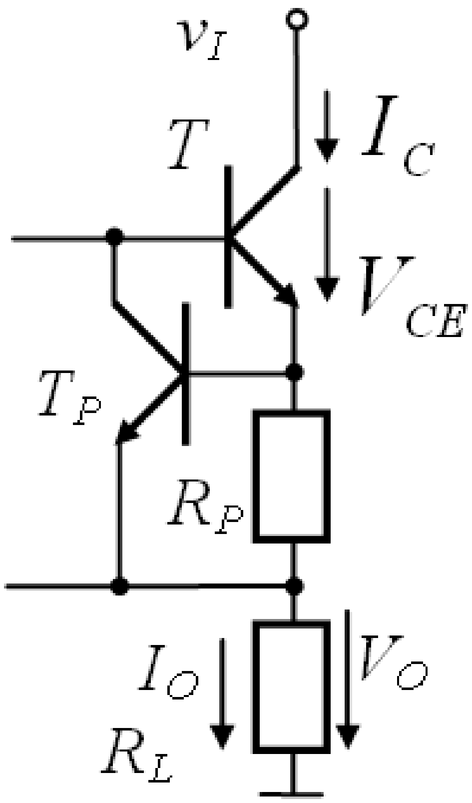
- short-circuit point

$$v_O = 0$$

$$I_O = I_{Osc} = \frac{0.7\text{V}}{R_p} + I_{O,AOmax} - \frac{1}{\beta}\frac{0.7V}{R_p} \approx \frac{0.7\text{V}}{R_p} + I_{O,AOmax} \approx \frac{0.7\text{V}}{R_p}$$

Maximum values of voltage, current, and power for *T*

$$v_I \in \left(V_{I\min} ; V_{I\max}\right)$$



- **maximum collector current:** $I_{O\max}$
- **maximum collector-emitter voltage**

$$V_{CE} = V_I - V_{R_P} - V_O$$

$V_{CE\max}$ appears for short-circuit to the output

$$V_{CEmax} = V_{Imax} - V_{R_p} = V_{Imax} - 0.7\text{V} \approx V_{Imax}$$

$$V_{CE\max} \approx V_{I\max}$$

- **maximum power dissipated by the transistor**

$$P_{dT} \approx I_C V_{CE}$$

$$P_{dT\max} \approx I_{O\max} V_{I\max}$$

appears for short-circuit to the output

Selecting the series pass transistor

In the transistor data-sheets we can find absolute maximum ratings for

- collector current $I_{C\max}$
- collector-emitter voltage V_{CE0}
- power $P_{d\,\mathrm{tot}}$

T should be selected so that:

$$I_{C\max} > 2I_{O\max}$$

$$V_{CE0} > V_{CE\max}$$

$$0.4P_{d\,\mathrm{tot}} \geq P_{dT\max}$$

Pay attention for dissipated power. The value in the data-sheet refers to the maximum power when *T* is mounted on an infinite area heatsink. In practice the maximum power to be consider is $P_{d\max} \approx 0,4P_{d\mathrm{tot}}$ (acceptable size heatsink).

2N3055(NPN), MJ2955(PNP)

Preferred Device

Complementary Silicon Power Transistors

Complementary silicon power transistors are designed for general−purpose switching and amplifier applications.

Features

- DC Current Gain − h_{FE} = 20−70 @ I_C = 4 Adc
- Collector−Emitter Saturation Voltage −
  $V_{CE(sat)}$ = 1.1 Vdc (Max) @ I_C = 4 Adc
- Excellent Safe Operating Area
- Pb−Free Packages are Available*

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector−Emitter Voltage	V_{CEO}	60	Vdc
Collector−Emitter Voltage	V_{CER}	70	Vdc
Collector−Base Voltage	V_{CB}	100	Vdc
Emitter−Base Voltage	V_{EB}	7	Vdc
Collector Current − Continuous	I_C	15	Adc
Base Current	I_B	7	Adc
Total Power Dissipation @ T_C = 25°C Derate Above 25°C	P_D	115 0.657	W W/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	−65 to +200	°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.

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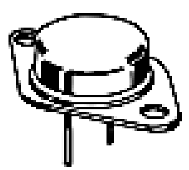
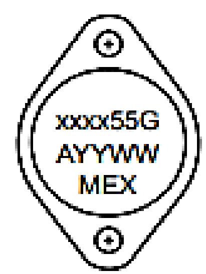
15 AMPERE
POWER TRANSISTORS
COMPLEMENTARY SILICON
60 VOLTS, 115 WATTS

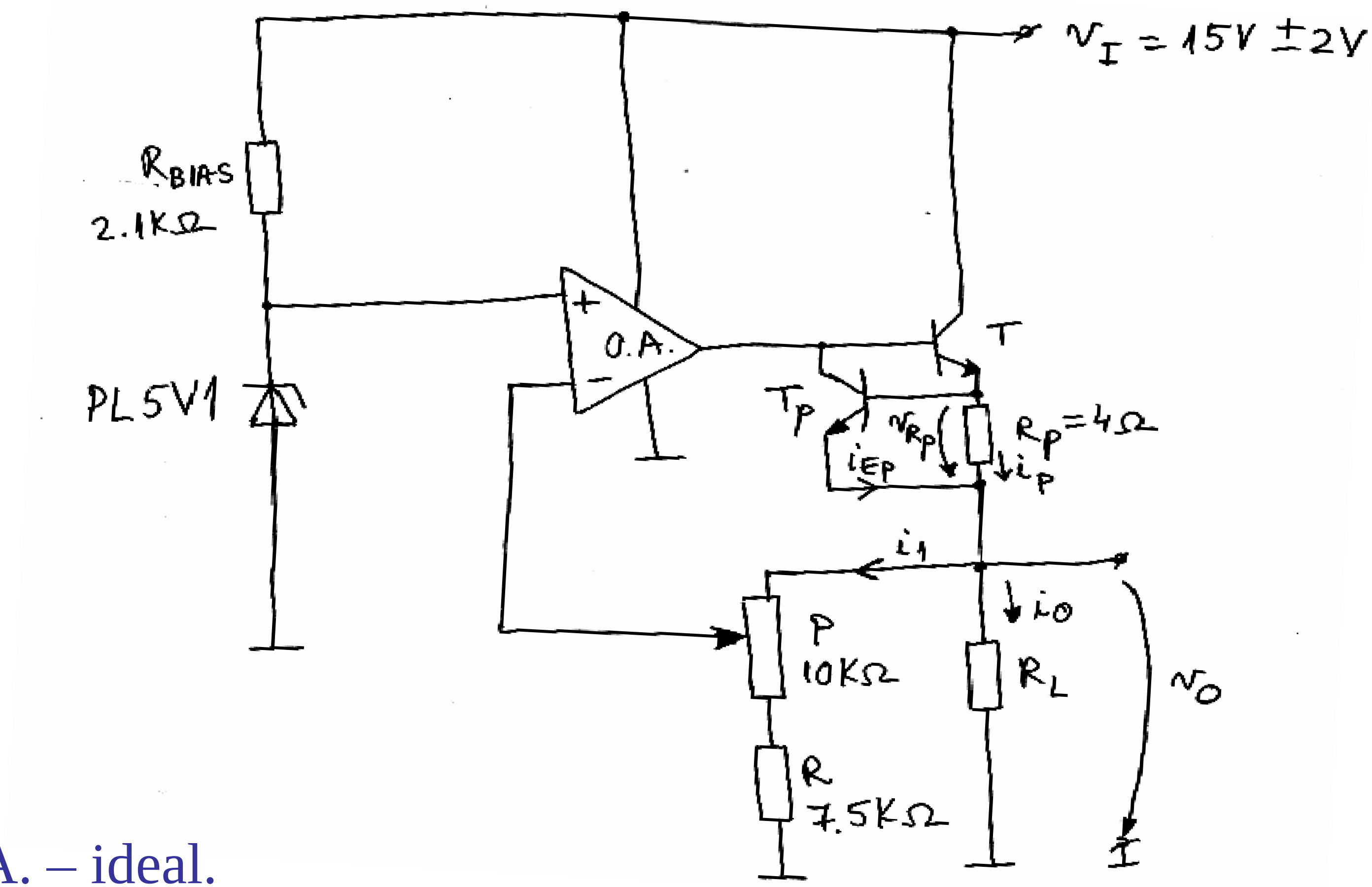


TO−204AA (TO−3)
CASE 1−07
STYLE 1

MARKING DIAGRAM



Exercise



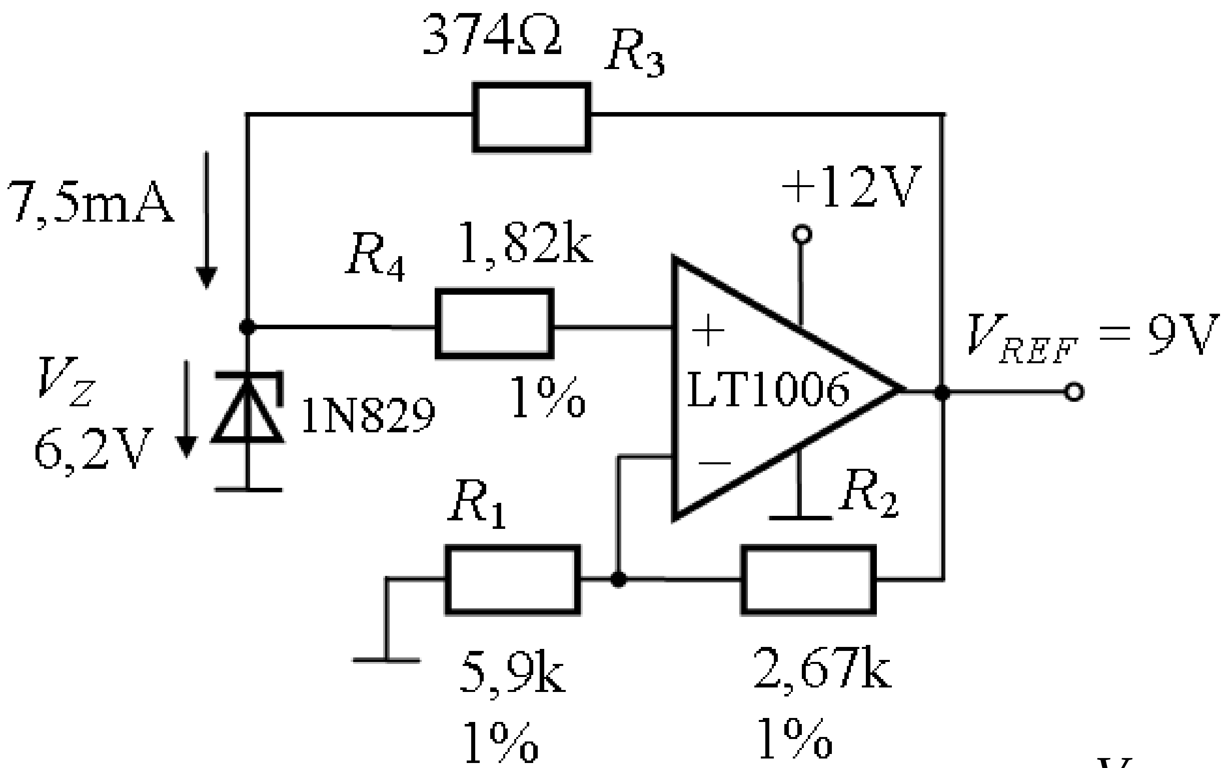
Consider the O.A. – ideal.

a)Find the expression and range of values in which V_O can be adjusted if R_L is large enough to maintain T_p – off.

b)What components in the circuit compose the protection circuit?

c) What is the maximum value of the output current? Assume that the base currents of T and T_p can be neglected. Assuming the cursor of P in the middle, compute the maximum power dissipation on T for R_{L1}=0.2 kΩ; R_{L2}=20 Ω; R_{L3}=0 Ω.

Voltage reference



$$I_Z = \frac{V_{REF} - V_Z}{R_3} = \frac{9 - 6.3}{374} = 7.5\text{mA}$$

$$V_{REF} = \left(1 + \frac{R_2}{R_1}\right) V_Z = \left(1 + \frac{2{,}67}{5.9}\right) \cdot 6.2 = 9\text{V}$$