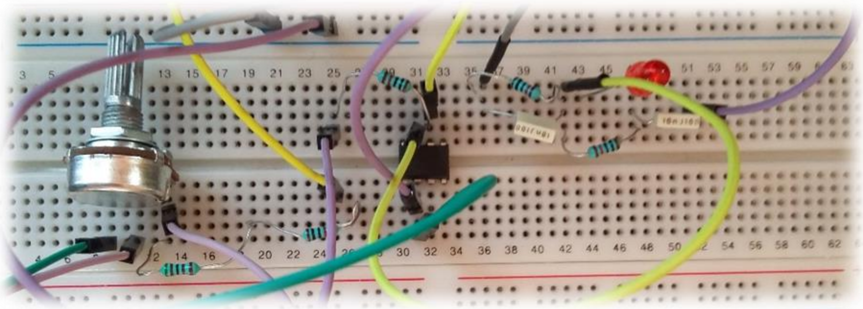


FUNDAMENTAL ELECTRONIC CIRCUITS

Assist. prof. Laura-Nicoleta IVANCIU, Ph.D.

C8 – DC voltage regulators

Contents

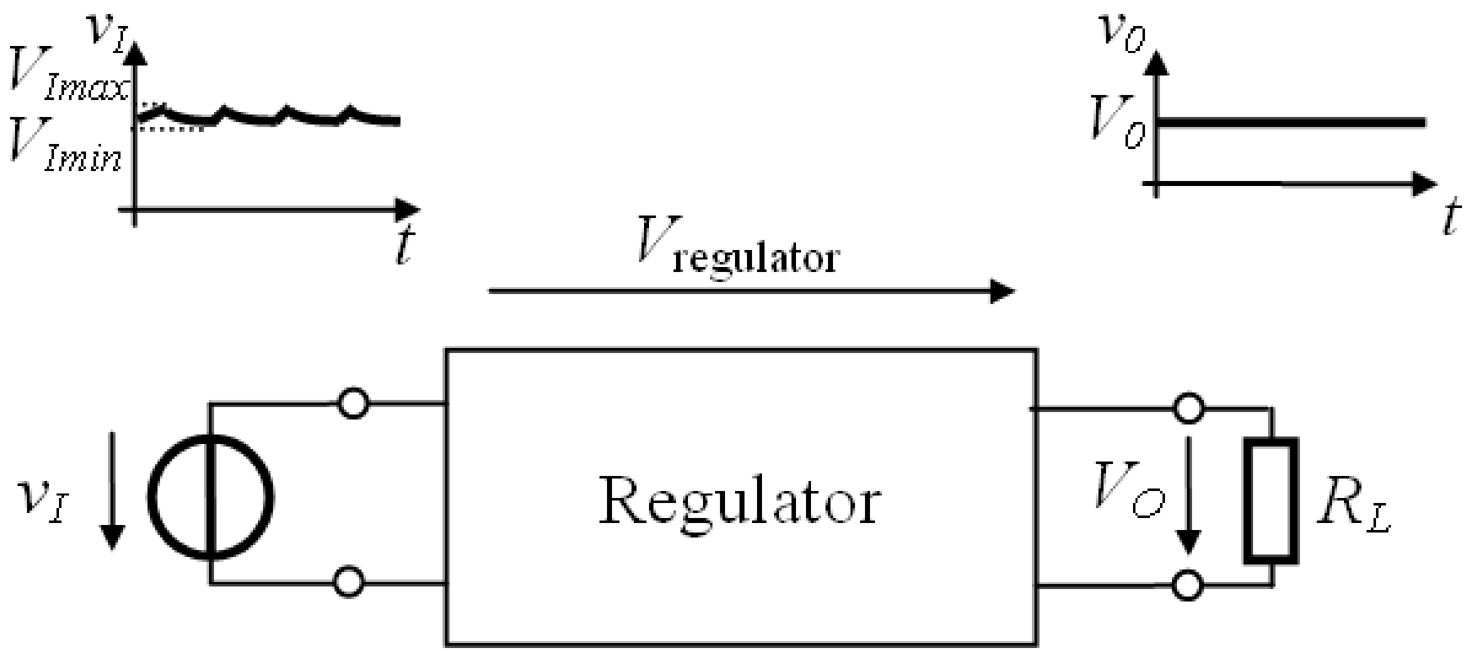
- Intro
- Parametric voltage regulators
- Linear voltage regulators

To begin with

- What is a voltage regulator? Where are voltage regulators used?
- What voltages (AC/DC) can be regulated? Is the output voltage AC or DC?
- What types of voltage regulators are there?

➢ Definition

A voltage regulator is an electronic circuit which maintains the output voltage (almost) constant despite reasonable changes in the input voltage, load, temperature, etc.



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

➢ Usage

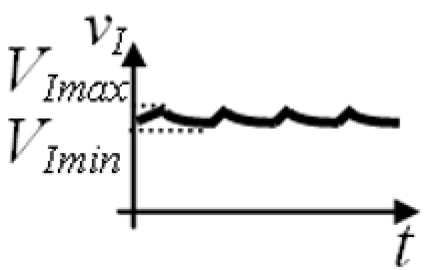
- to stabilize the input voltage in any electronical equipment (laptop, refrigerator, washing machine, TV set, etc)

Voltage regulators take a high, slightly variable input voltage, and deliver a lower, more stable and reliable output voltage.

- to protect against voltage spikes that may damage/destroy

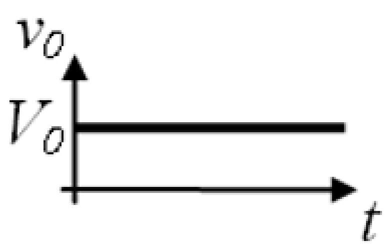
➢ Input and output voltages

- input voltage can be AC or DC



variation of v_I: $\Delta v_I = V_{Imax} - V_{Imin}$

- output voltage is DC (constant, regulated, reliable output voltage)

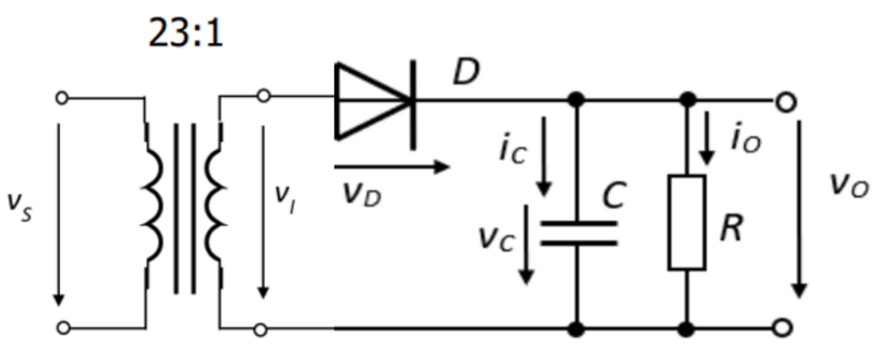


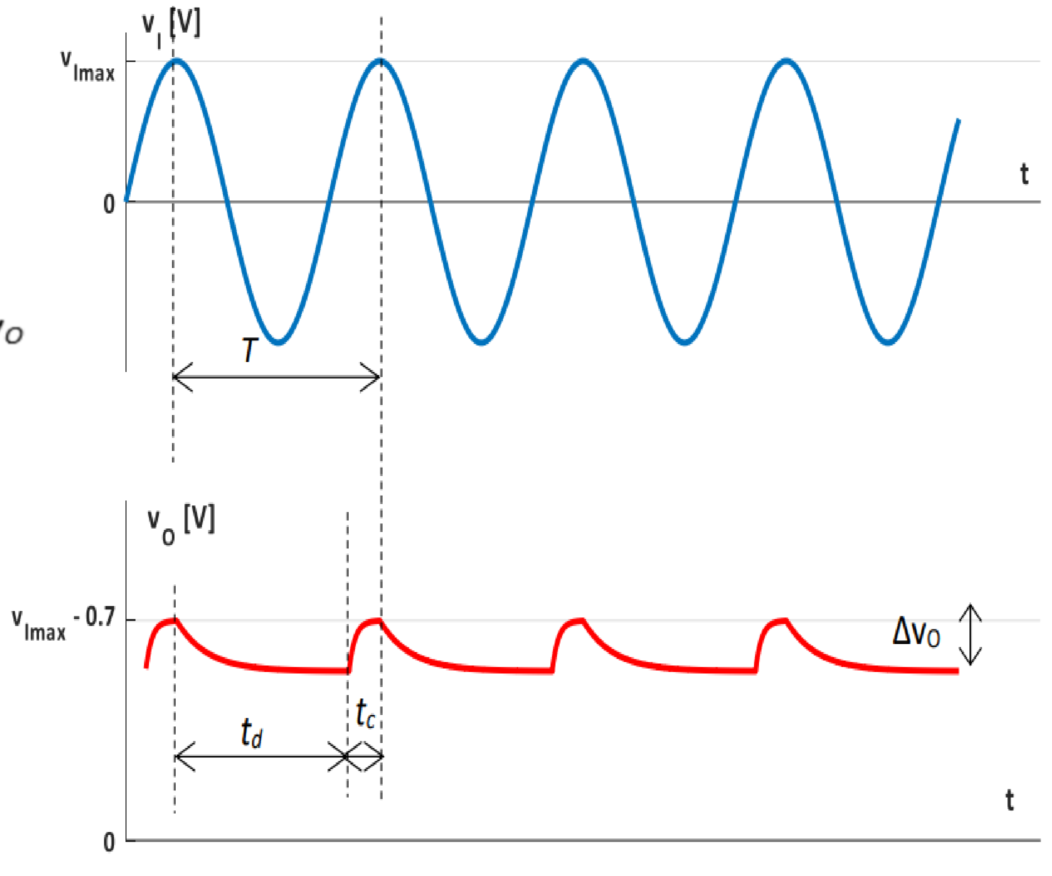
variation of v_O: $\Delta v_O = 0$ – ideally

variation of v_O: Δv_O [mV] – IRL

The bigger the allowed Δv_I, the better the voltage regulator.

➢ Sample (simple) voltage regulator





Δv_O – as small as possible

Types of voltage regulators

Based on the type of components:

- discrete: voltage regulators built w/ ZD, OpAmp, T, etc
- integrated: LM78xx, LM79xx, LM723, etc

Based on the devices they contain:

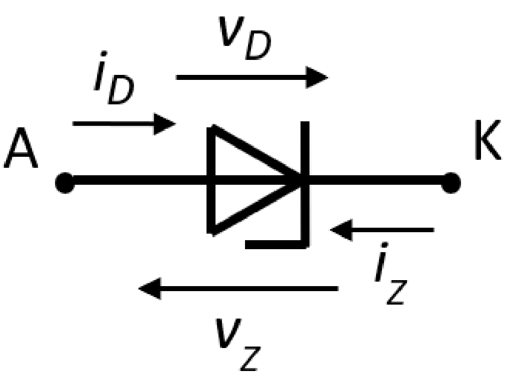
- parametric voltage regulators: w/ ZD
- active voltage regulators: w/ active devices (OpAmp, T)

Active voltage regulators can be:

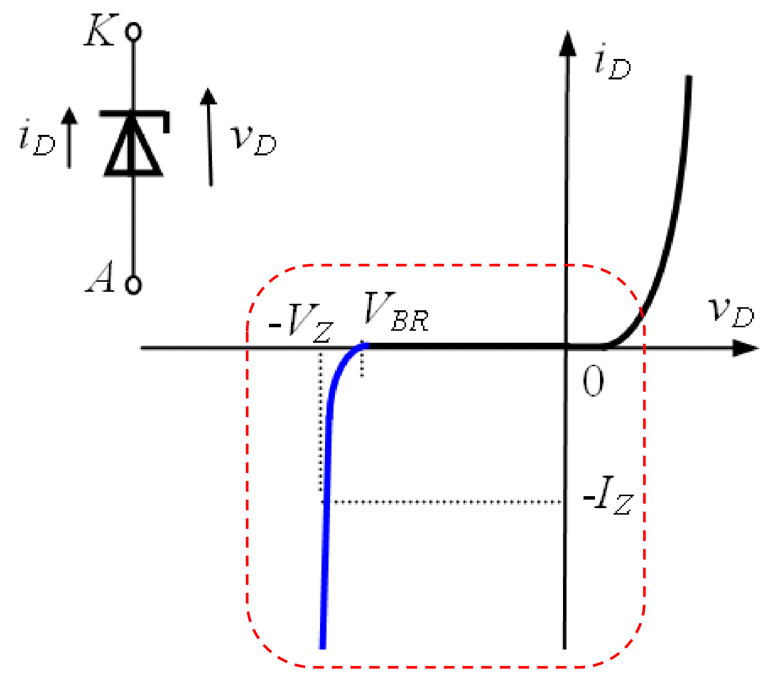
- linear: T is in linear region, OpAmp has NF
- switching (switched-mode): T is on/off, f ≥ 20 kHz, OpAmp has NF

➢ Zener diode - revisited

- ZDs are used in the breakdown region (regulation region) – 3rd quadrant
- working w/ positive values is usually preferred -> inverted I and V

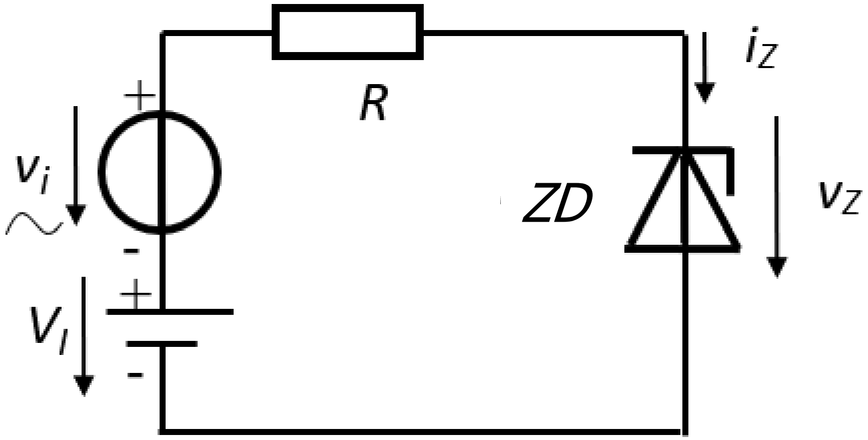


$$i_Z = -i_D$$
$$v_Z = -v_D$$



➢ Zener diode - revisited

- typically used for regulation purposes – ZD provides a constant V_Z , if I_Z stays between certain boundaries

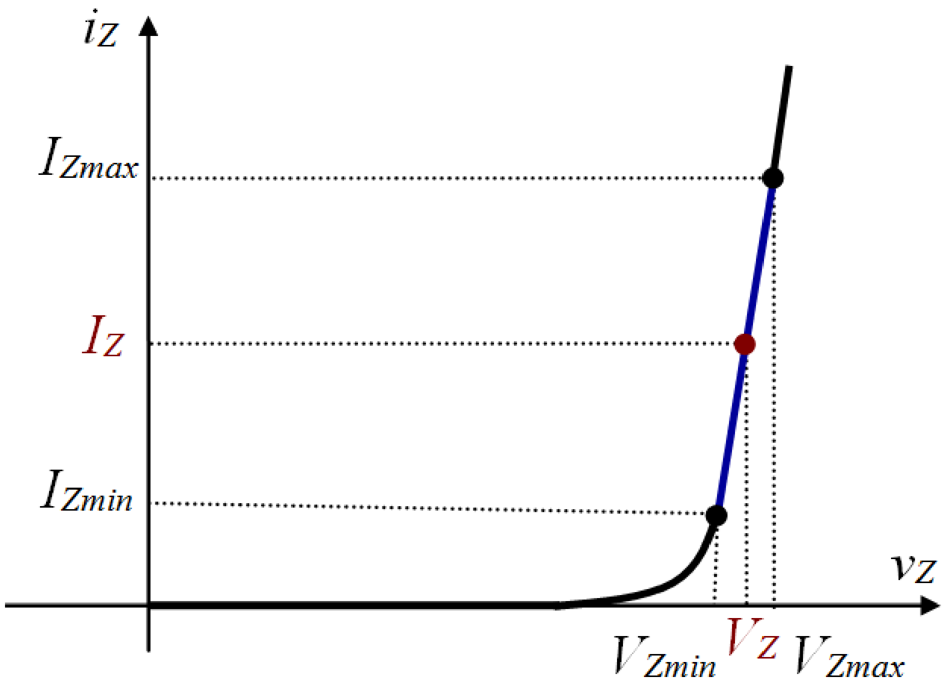


Relative regulation factor of ZD – ratio between dynamic and static equivalent resistances

$$F_Z = \frac{r_z}{r_Z}$$

$$F_Z = \frac{\frac{\Delta v_Z}{V_Z}}{\frac{\Delta i_Z}{I_Z}}$$

➢ Zener diode - revisited



Datasheet of a ZD:

$P_{dmax}, V_Z@I_Z$

$$I_{Z\,max} = \frac{P_{dmax}}{V_{Zmax}}$$

Good enough - $I_{Z\,max} = \frac{P_{dmax}}{V_Z}$

To maintain ZD in its regulation region

$$I_{Z\,min} < I_Z < I_{Z\,max}$$

Zener diode - revisited

FAIRCHILD SEMICONDUCTOR®

1N4728A - 1N4758A
Zener Diodes

Tolerance = 5%

DO-41 Glass case
COLOR BAND DENOTES CATHODE

$$P_{dmax} = 1\ \mathrm{W}$$

$$I_{Z\,max} = \frac{P_{dmax}}{V_Z}$$

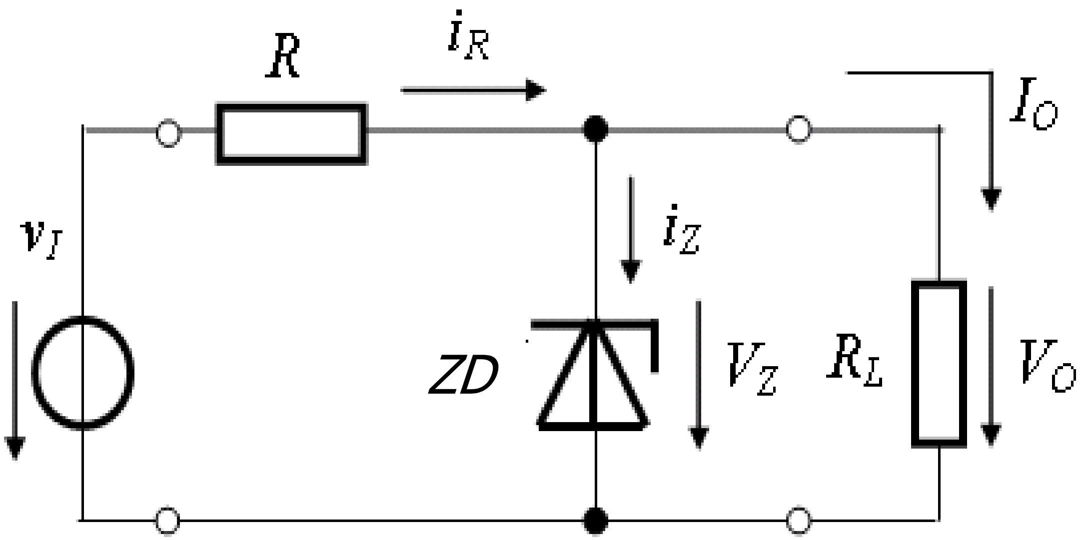
Electrical Characteristics T_a = 25°C unless other

Device	V_Z (V) @ I_Z (Note 1)			Test Current I_Z (mA)
	Min.	Typ.	Max.	
1N4728A	3.135	3.3	3.465	76
1N4729A	3.42	3.6	3.78	69
1N4730A	3.705	3.9	4.095	64
1N4731A	4.085	4.3	4.515	58
1N4732A	4.465	4.7	4.935	53
1N4733A	4.845	5.1	5.355	49
1N4734A	5.32	5.6	5.88	45
1N4735A	5.89	6.2	6.51	41
1N4736A	6.46	6.8	7.14	37
1N4737A	7.125	7.5	7.875	34
1N4738A	7.79	8.2	8.61	31
1N4739A	8.645	9.1	9.555	28
1N4740A	9.5	10	10.5	25
1N4741A	10.45	11	11.55	23
1N4742A	11.4	12	12.6	21

1N4728A - 1N4758A Rev. H3

➢ Circuit and operation

- uses the nonlinear current-voltage characteristic of ZD



$$V_O = V_Z$$

$$v_I \in [V_{Imin}; V_{Imax}]$$

$$I_O \in [I_{Omin}; I_{Omax}]$$

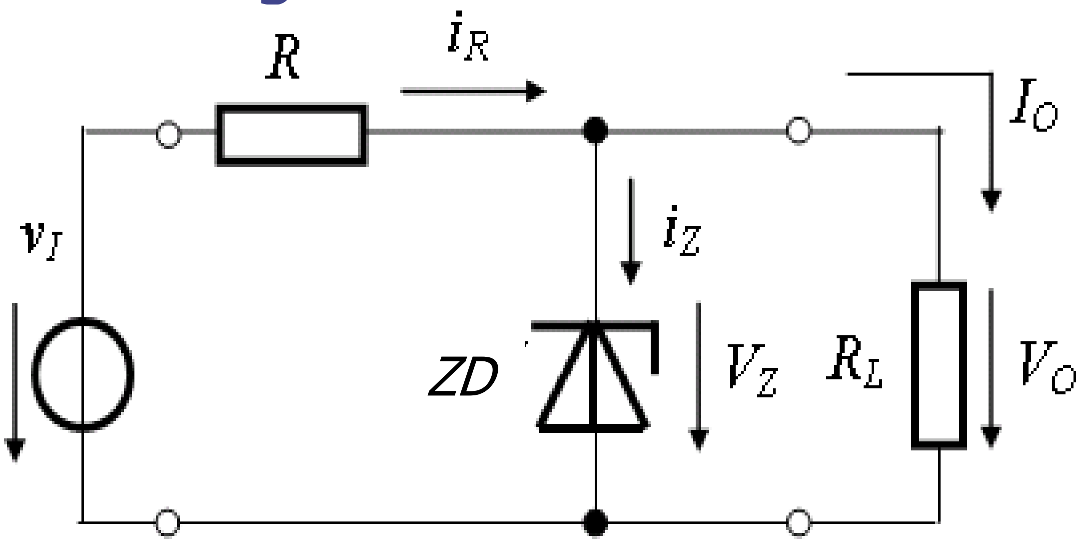
⬇

$$i_Z \in [I_{Zmin}; I_{Zmax}]$$

Regulation mechanism:

$$\boldsymbol{V_O} \uparrow, I_O \uparrow, i_Z \downarrow, V_Z \downarrow, \boldsymbol{V_O} \downarrow$$

➢ Sizing R



Design data:

$v_I \in (v_{Imin}, v_{Imax})$
V_O
$R_L \in (R_{Lmin}, R_{Lmax})$

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

$$I_{Omin} = \frac{V_Z}{R_{Lmax}} \qquad I_{Omax} = \frac{V_Z}{R_{Lmin}}$$

Worst case:

$$I_{Zmax} = i_{Rmax} - I_{Omin} = \frac{v_{Imax} - V_Z}{R_{min}} - I_{Omin}$$

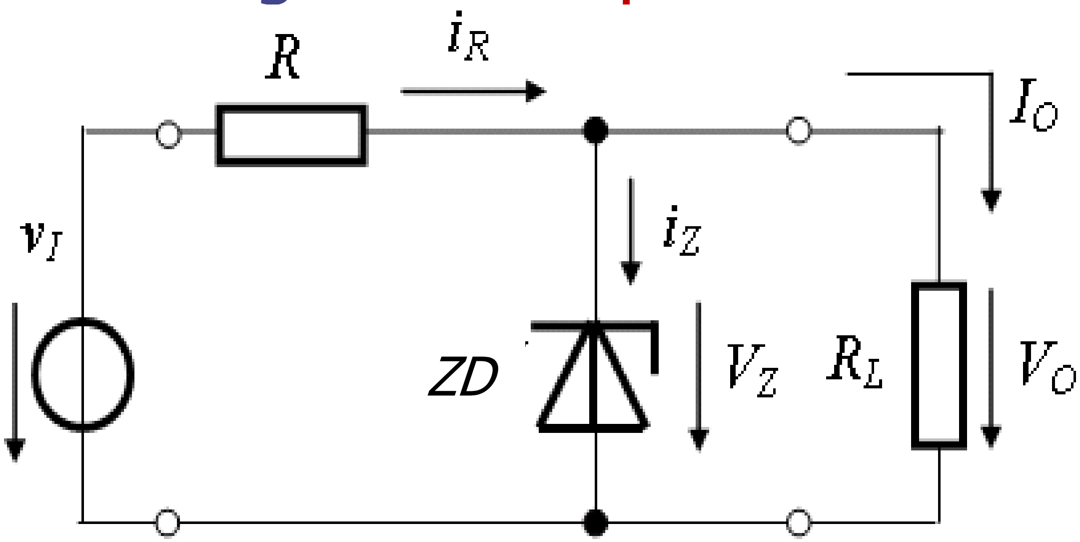
$$I_{Zmin} = i_{Rmin} - I_{Omax} = \frac{v_{Imin} - V_Z}{R_{max}} - I_{Omax}$$

$$R_{max} = \frac{v_{Imin} - V_Z}{I_{Zmin} + I_{Omax}}$$

$$R_{min} = \frac{v_{Imax} - V_Z}{I_{Zmax} + I_{Omin}}$$

$$R \in (R_{min};\ R_{max})$$

➢ Sizing R - example



Design data:

$v_I = 12 \pm 0.5$ V
$V_O = 7.5$ V
$I_O = [25, 50][\mathrm{mA}]$
$R = ?$
$i_Z = ?$ for $v_I = 12$ V, $I_O = 40$ mA

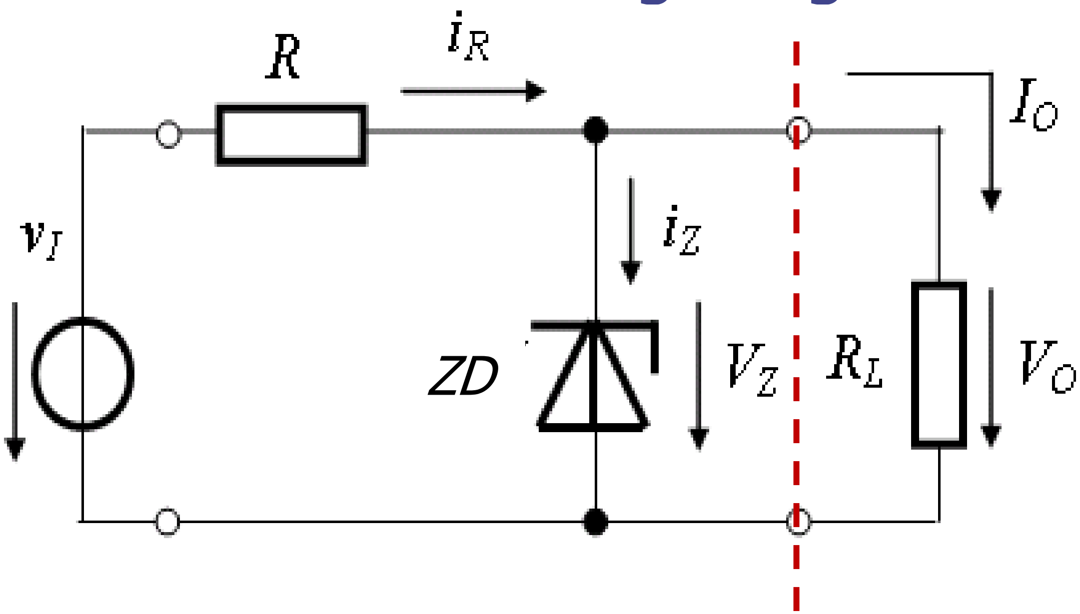
Choose suitable ZD from the datasheet: 1N4737A, $V_O = 7.5$ V @ 34 mA, $P = 1$ W

$$I_{Z\,max} = \frac{P_{dmax}}{V_Z} = 133 \text{ mA}$$

Assume $I_{zmin} = 20$ mA: $R_{max} = \frac{v_{Imin} - V_Z}{I_{Zmin} + I_{Omax}} = 57\ \Omega$ $R_{min} = \frac{v_{Imax} - V_Z}{I_{Zmax} + I_{Omin}} = 31.6\ \Omega$

Choose $R = 47\ \Omega$: $i_Z = i_R - I_O = \frac{v_I - V_Z}{R} - I_O = 40\ mA$

➢ Parametric voltage regulator - summary



ZD is kept in the regulation region if:

$$R_{max} = \frac{v_{Imin} - V_Z}{I_{Zmin} + I_{Omax}}$$

$$R_{min} = \frac{v_{Imax} - V_Z}{I_{Zmax} + I_{Omin}}$$

Drawback:

If $V_O = V_Z$=const., a change in R_L means a change in I_O, which impacts i_Z

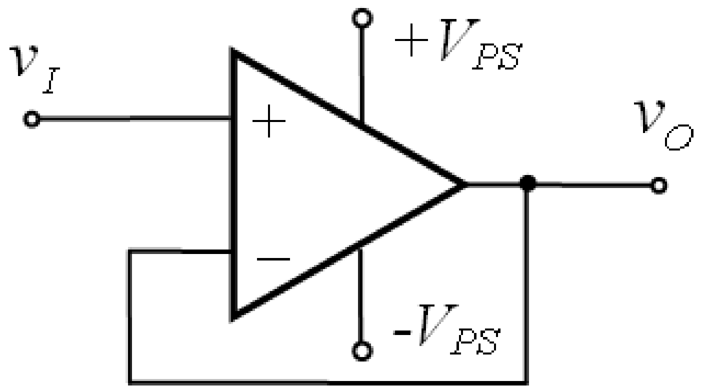
$$i_Z = i_R - I_O$$

Solution?

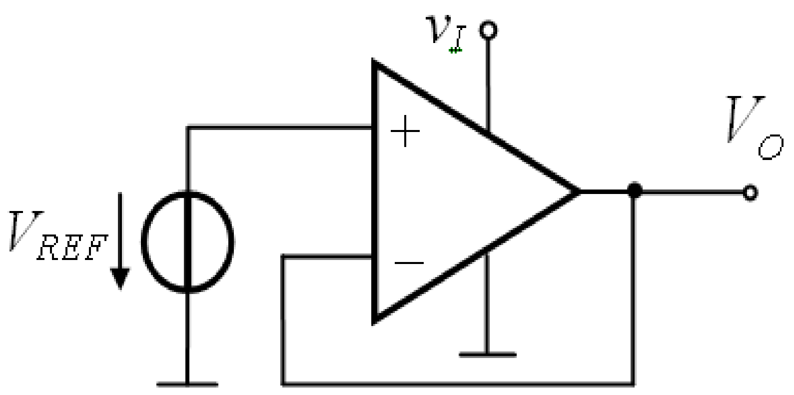
Voltage follower (buffer, current amplifier) between *ZD* and R_L

➢ Solutions to the drawback

Voltage follower (buffer, current amplifier) between *ZD* and R_L



Voltage follower w/ OpAmp



Voltage regulator w/ OpAmp

$$v_O = v_I$$

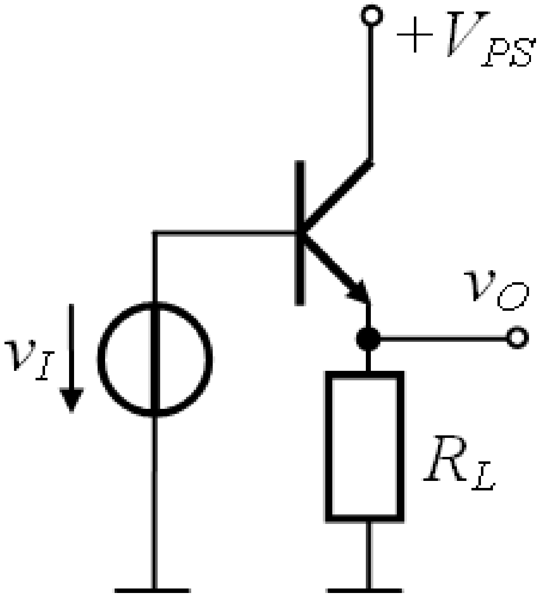
$$V_O = V_{REF}$$

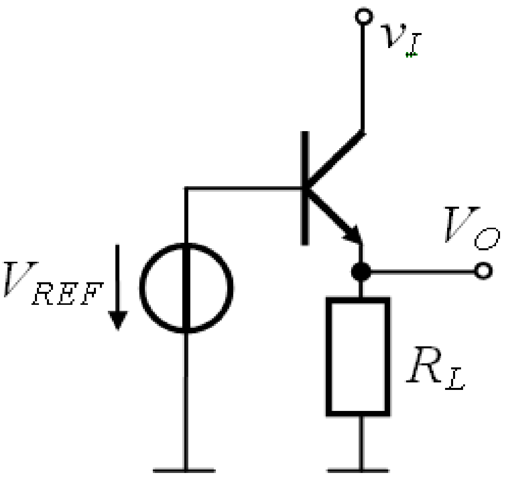
v_I – used as supply

V_{REF} – voltage obtained from *ZD*

Solutions to the drawback

Voltage follower (buffer, current amplifier) between *ZD* and R_L





Voltage follower w/ BJT

$$v_O = v_I - v_{BE}$$

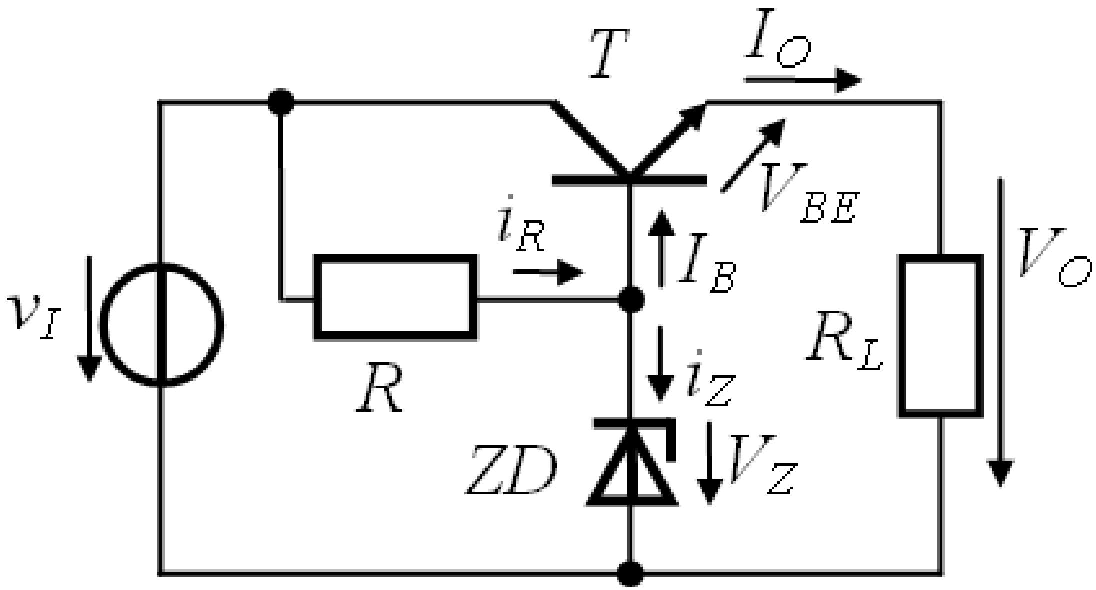
Voltage regulator w/ BJT

$$V_O = V_{REF} - v_{BE}$$

v_I – used as supply

V_{REF} – voltage obtained from *ZD*

BJT voltage regulator – circuit and operation



T – series pass transistor

$$V_O = V_Z - v_{BE}$$

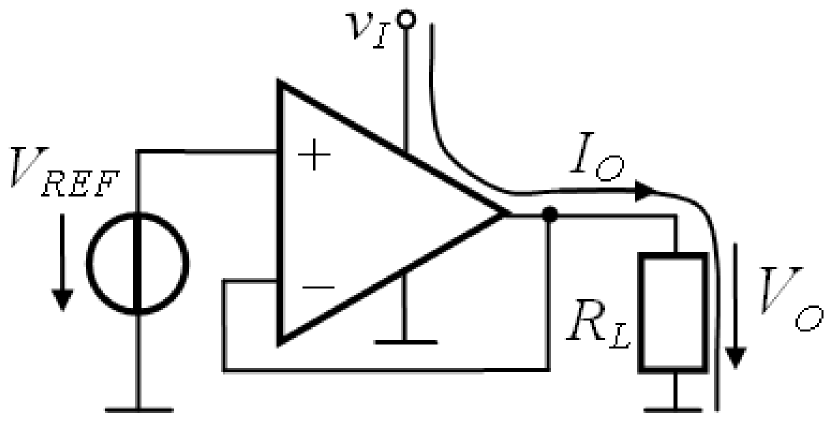
$$i_Z = i_R - I_B = i_R - \frac{I_O}{\beta}$$

Regulation mechanism:

$$\boldsymbol{V_O} \downarrow, I_O \downarrow, I_B \downarrow, i_Z \uparrow, V_Z \uparrow, \boldsymbol{V_O} \uparrow$$

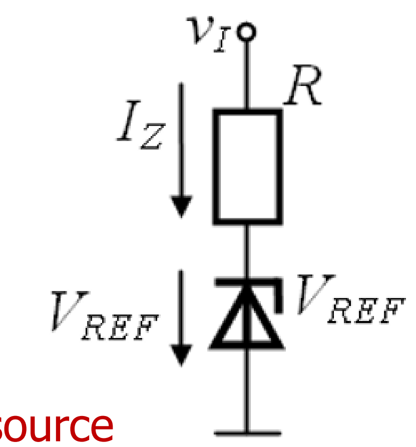
$\boldsymbol{V_O}$ is kept constant through NF

➢ OpAmp voltage regulator – circuit and operation



$V_O = V_{REF}$

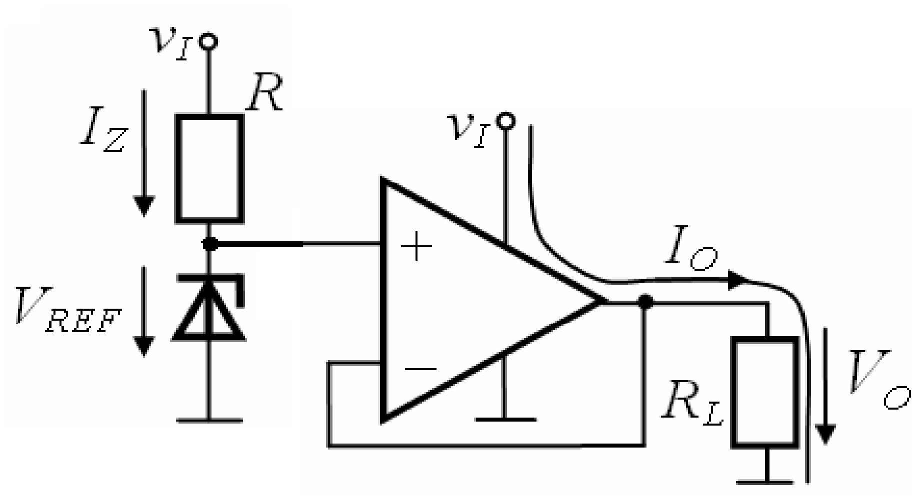
To obtain V_{REF}



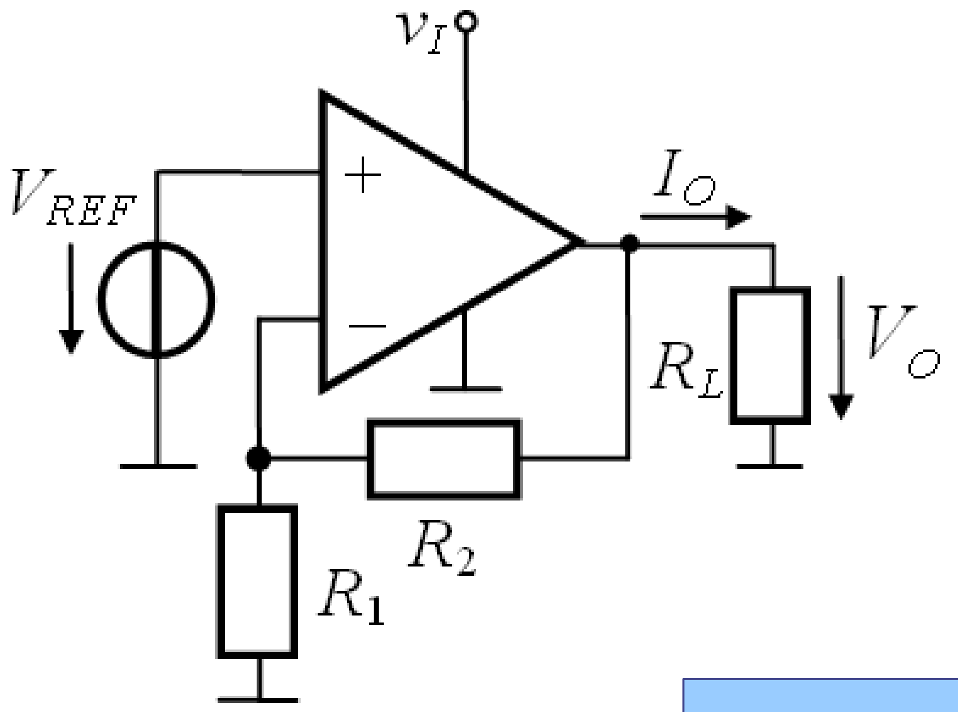
For better regulation:

replace *R* w/ a current source

Final circuit:

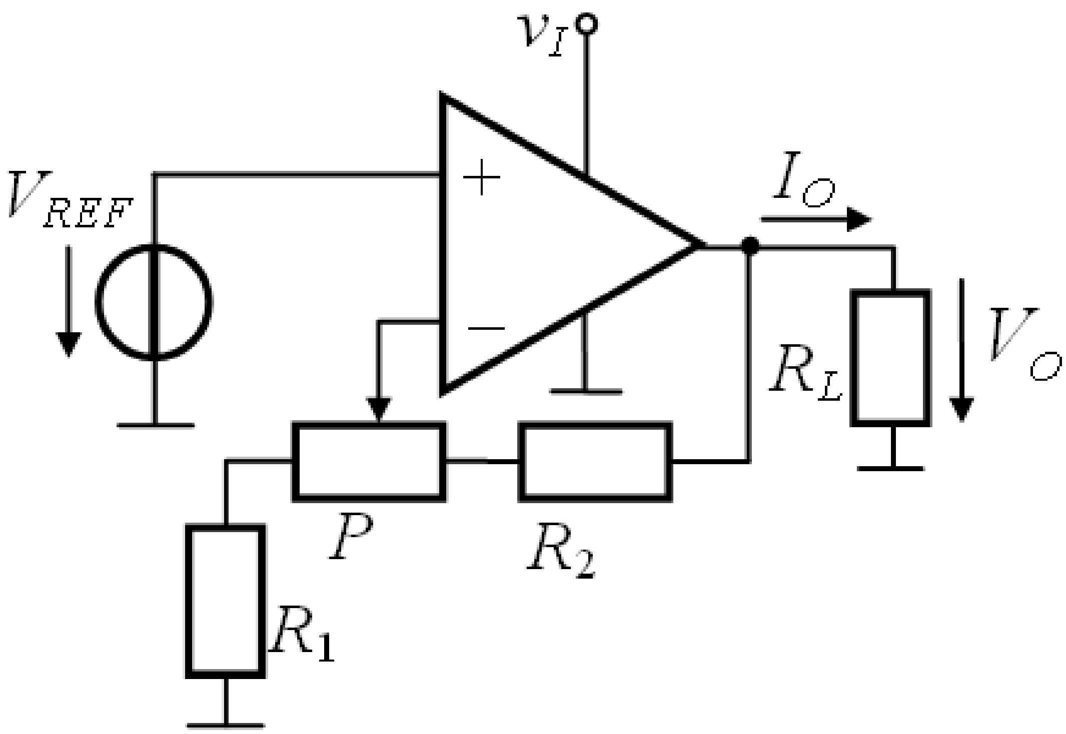


- OpAmp voltage regulator – $V_O > V_{REF}$, fixed V_O



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

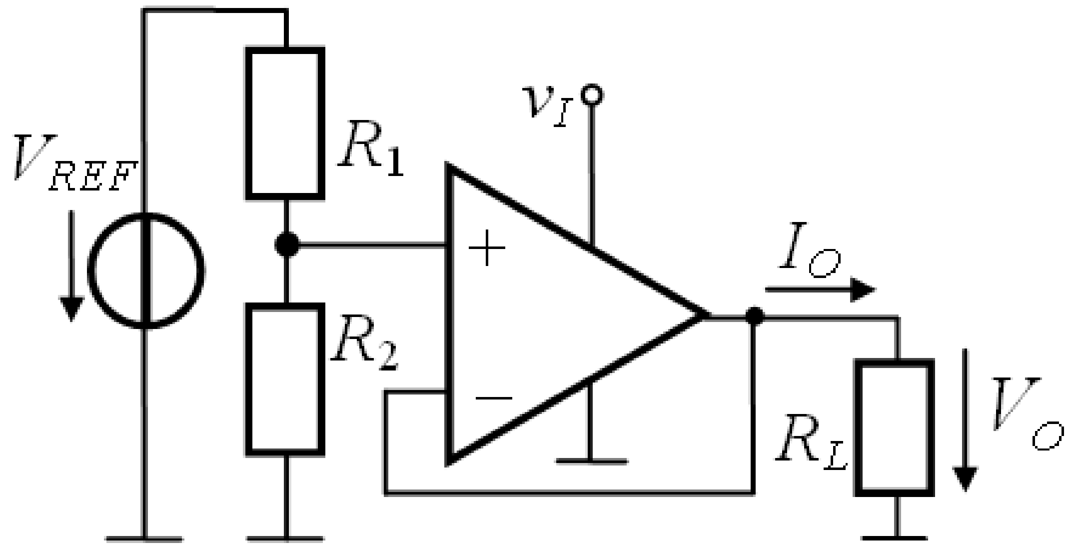
- OpAmp voltage regulator – $V_O > V_{REF}$, adjustable V_O



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

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

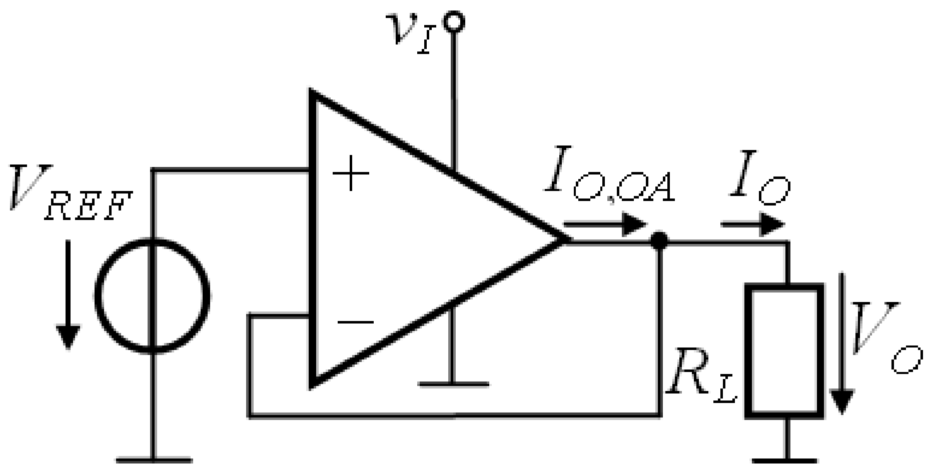
- OpAmp voltage regulator – $V_O < V_{REF}$, fixed V_O



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

Circuit for $V_O < V_{REF}$, adjustable V_O? $V_{Omin} = ?\, V_{Omax} = ?$ See L9

➢ Increasing the output current I_O



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

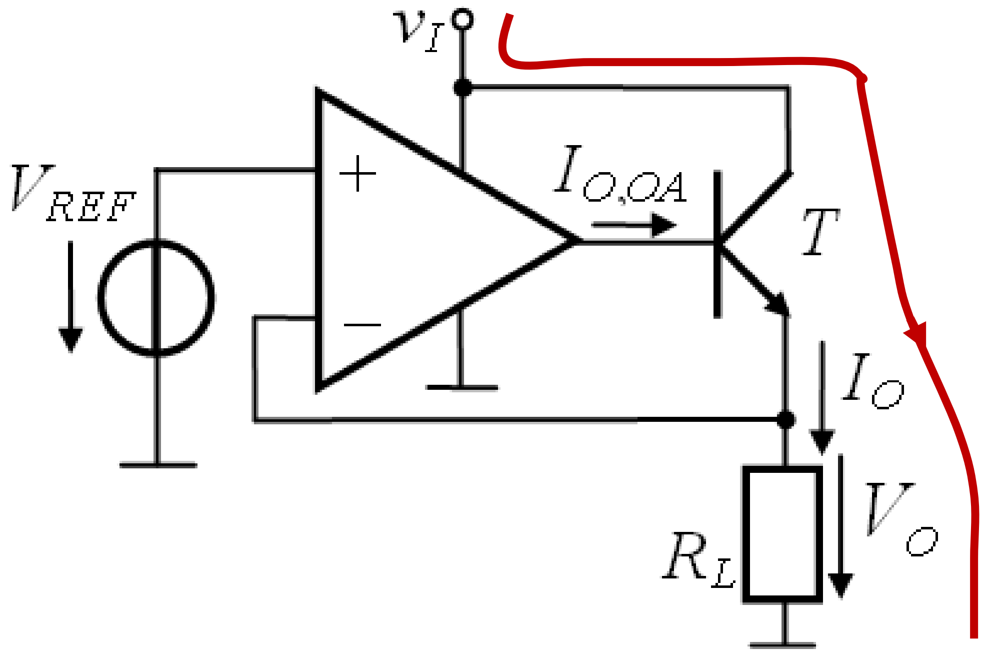
Common purpose OpAmp:

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

Solutions for a higher output current?

- power OpAmps (e.g. TDA2030 $I_{O,OA\,max} = 3.5\ \text{A}$, OPA549 $I_{O,OA\,max} = 8\ \text{A}$)
- current amplifier between OpAmp and load resistance

➢ Increasing the output current I_O



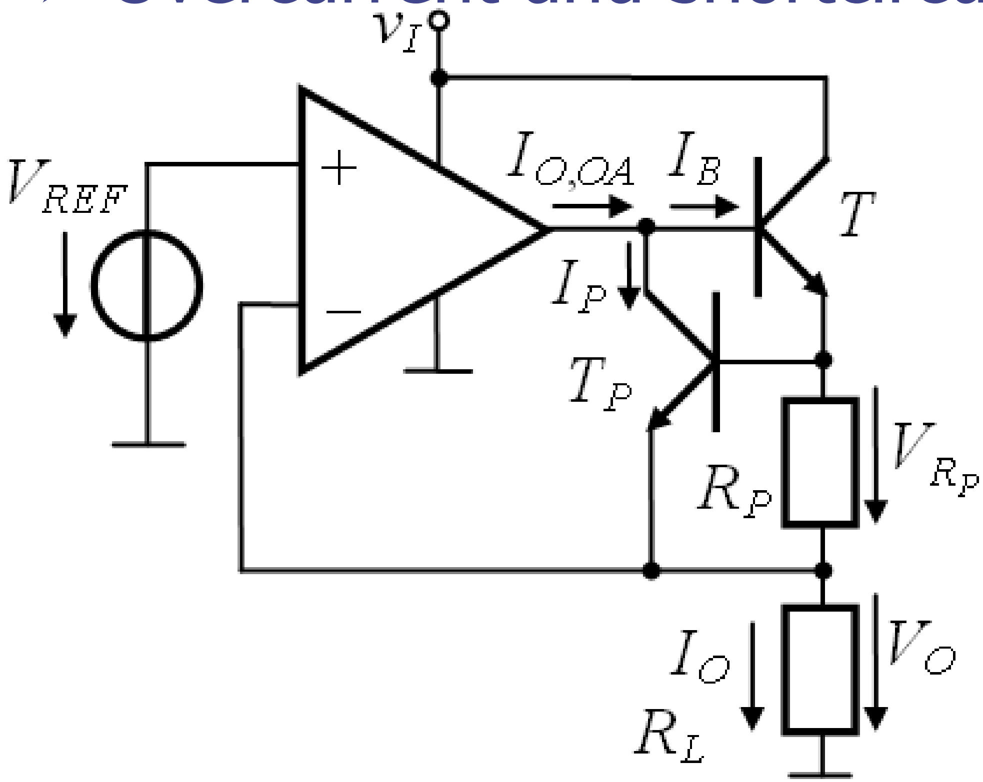
$$I_O = \beta I_{O,OA}$$

T – series pass transistor

- How much can I_O increase?
- What happens if R_L (accidentally or on purpose) becomes 0 (shortcircuit)?

Idea: do something to prevent overcurrent and shortcircuit

Overcurrent and shortcircuit protection



T_p, R_p – protection circuit

$R_P I_O < 0.7\text{ V} \quad T_P - (off) \quad I_P = 0$

$R_P I_O > 0.7\text{ V} \quad T_P - (a_F) \quad I_P > 0$

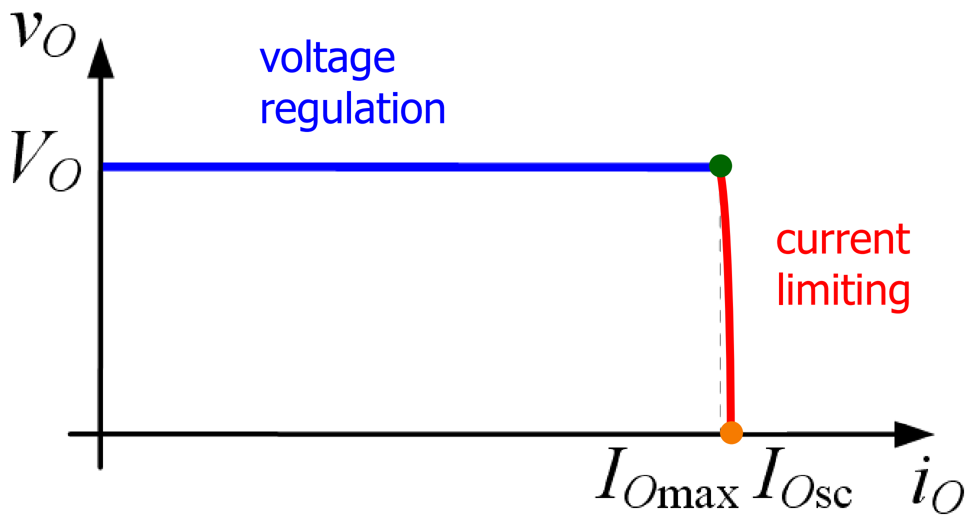
$$I_{Omax} = \frac{V_{R_P}}{R_p} + I_p = \frac{0.7\text{ V}}{R_p} + I_p \approx \frac{0.7\text{ V}}{R_p}$$

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

I_{Omax} is set by sizing R_p

Protection mechanism $R_L \downarrow,\ I_O \uparrow,\ I_O R_P \uparrow,\ I_P \uparrow,\ I_B \downarrow,\ I_O \downarrow$

➢ The $v_O(i_O)$ output characteristic



- voltage regulation region

$$v_O = V_O \qquad I_O = \frac{V_O}{R_L}$$

- knee point

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

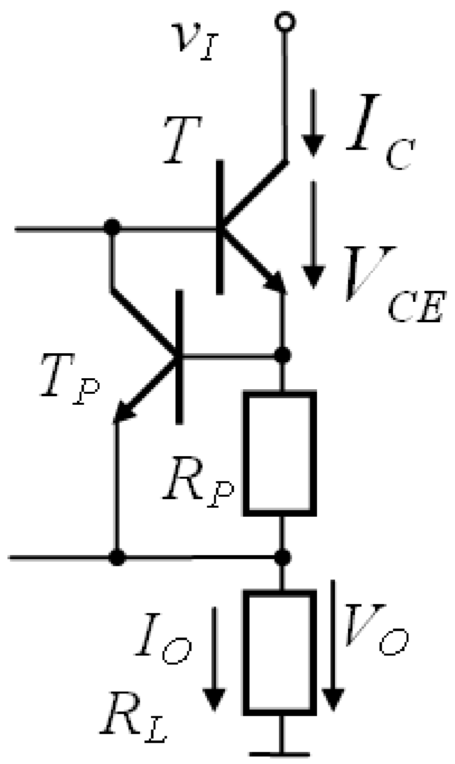
- current limiting region

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

- short-circuit point

$$v_O = 0 \qquad I_O = I_{Osc} = \frac{0.7\text{ V}}{R_p} + I_{O,OA\,max} - \frac{1}{\beta}\frac{0.7\text{ V}}{R_p} \approx \frac{0.7\text{ V}}{R_p} + I_{O,OA\,max} \approx \frac{0.7\text{ V}}{R_p}$$

➢ Maximum voltage/current/power dissipation on *T*



$v_I \in (V_{Imin};\ V_{Imax})$

- maximum collector current: $I_{Cmax} = I_{Omax}$
- maximum collector-emitter voltage

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

V_{CEmax} appears for shortcircuit at the output ($R_L = 0$, $V_O = 0$)

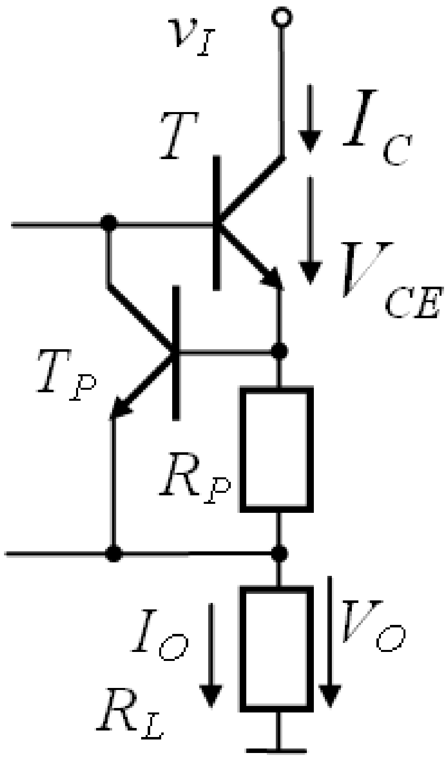
$$V_{CEmax} = V_{Imax} - V_{R_p} = V_{Imax} - 0.7 \approx V_{Imax}$$

- maximum power dissipated by the transistor

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

P_{dTmax} appears for shortcircuit at the output ($R_L = 0$, $V_O = 0$) $\quad P_{dTmax} \approx I_{Omax} V_{Imax}$

➢ Selecting the series pass transistor *T*



Values from the datasheet – absolute maximum ratings:

- collector current I_{Cmax}
- collector-emitter voltage V_{CEO}
- total dissipated power P_{dtot} - assuming infinite heatsink

Select *T* so that

$$I_{Cmax} > 2I_{Omax}$$

$$V_{CEO} > V_{CEmax}$$

$$0.4P_{dtot} \geq P_{dTmax}$$

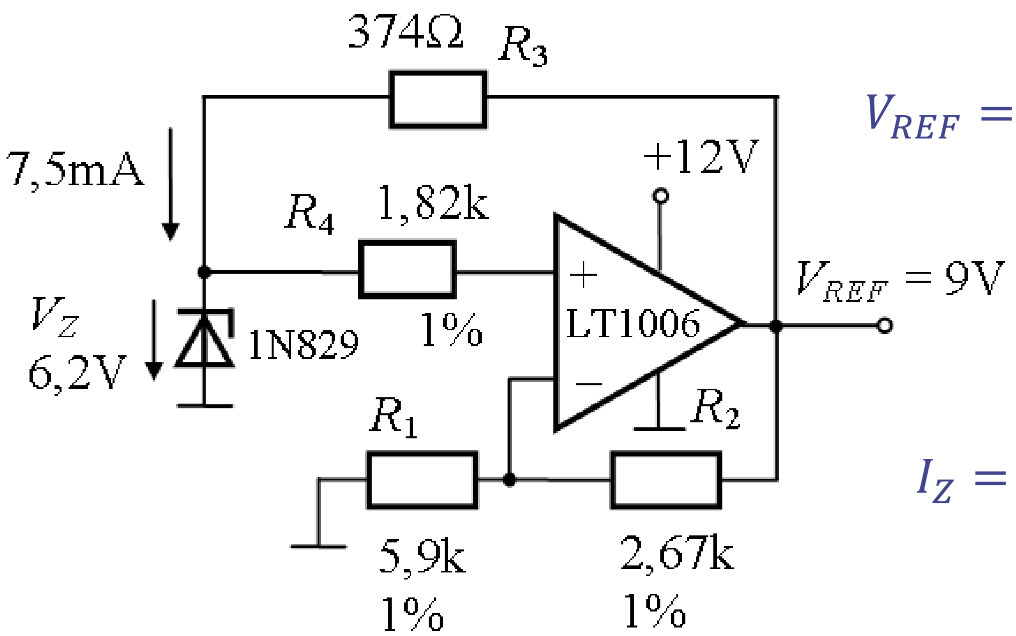
➢ Selecting the series pass transistor *T* - example

Table 2. Absolute maximum rating

Symbol	Parameter	Value		Unit
		NPN	2N3055	
		PNP	MJ2955	
V_{CBO}	Collector-base voltage ($I_E = 0$)	100		V
V_{CER}	Collector-emitter voltage ($R_{BE} = 100\ \Omega$)	70		V
V_{CEO}	Collector-emitter voltage ($I_B = 0$)	60		V
V_{EBO}	Emitter-base voltage ($I_C = 0$)	7		V
I_C	Collector current	15		A
I_B	Base current	7		A
P_{TOT}	Total dissipation at $T_c \leq 25°C$	115		W
Tstg	Storage temperature	-65 to 200		°C
TJ	Max. operating junction temperature	200		°C

Obtaining V_{REF} – alternative method

- 1N829 – temperature compensated Zener diode
- better option for obtaining V_{REF} than the simple circuit w/ *ZD* and *R* or *ZD* and current source
- stable w/ respect to temperature variations

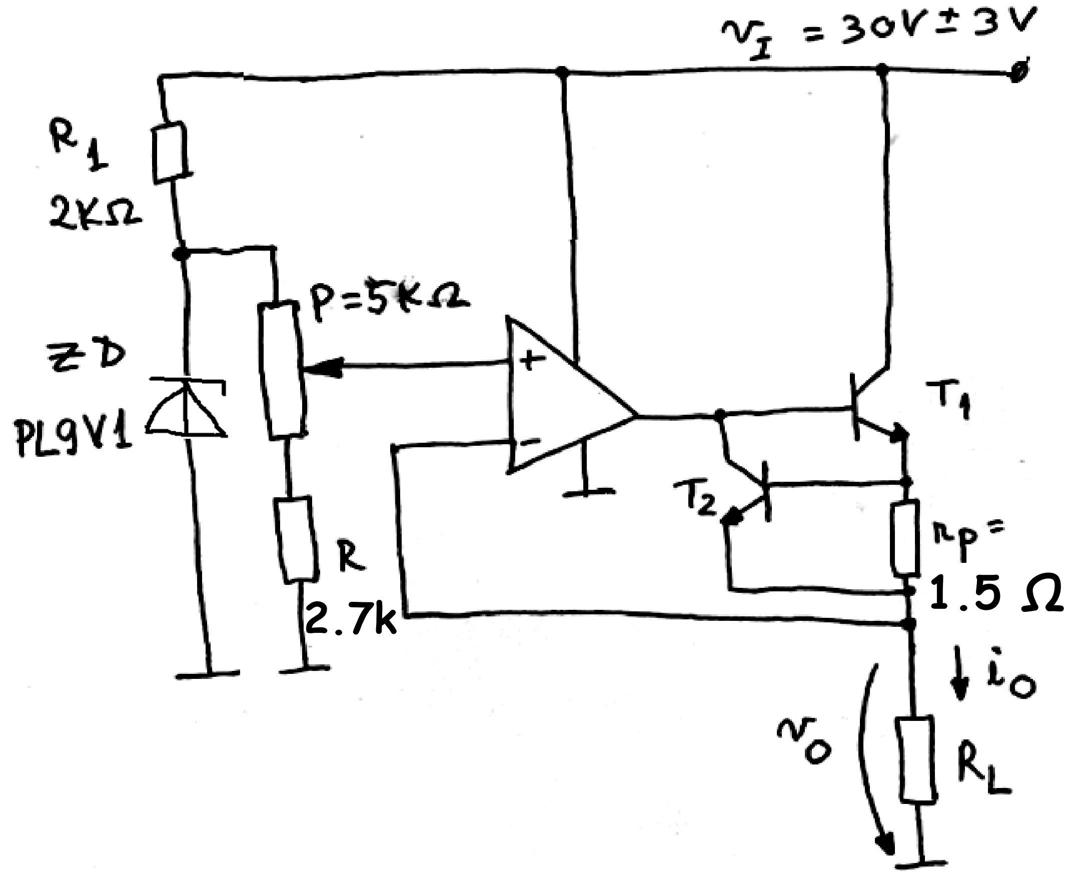


voltage reference circuit

$$V_{REF} = \left(1 + \frac{R_2}{R_1}\right) V_Z = \left(1 + \frac{2.67}{5.9}\right) \cdot 6.2 = 9 \text{ V}$$

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

➢ Example



a) Current through the Zener diode?
b) V_O range?
c) Plot $v_O(i_O)$ considering the tap to the middle position.
d) Compute the maximum power dissipated by T_1 for

$R_L = 500\ \Omega$; $R_L = 14\ \Omega$; shortcircuit when:

i) the tap is in the top position
ii) the tap is in the middle position.

Summary

- Intro
- Parametric voltage regulators
- Linear voltage regulators

Next week: Integrated voltage regulators. Switched-mode power supplies.