Applied Electronics

E2 – Linear Voltage Regulators

- Parameters and structure
- Zener and parallel regulators
- Series regulators
- Integrated regulators

Lecture E2: Linear Voltage Regulators

- Power supply types and their parameters
- Parallel regulators: Zener diodes
- Series regulators
  - Transistor circuits
  - Circuits with operational amplifiers (and transistors)
- Integrated voltage regulators
  - Low Dropout Regulators (LDO)
- References
  - F. Maloberti: Understanding Microelectronics…, Chap. 13

Electrical energy converters

- Electrical energy: different forms
  - Ac (Alternate Current): alternating voltage (sinusoidal)
    - Supplied by alternators, distribution network, inverters, ...
  - Dc (Direct Current): direct voltage (constant voltage)
    - Supplied by batteries, solar cells, fuel-cells, dc power supplies
- Electrical energy converter
  - Transform one form of (electrical) energy into another, or into the same with other parameters
  - Objectives
    - Low losses / high yield
    - Well controlled output parameters (voltage, frequency, ...)
    - Protections (no damage to the load or the source)

Overall converter picture

- Ac → ac
  - Transformers
  - Converters (ac → dc → ac)
- Ac → dc
  - Power Supplies
- Dc → ac
  - Inverter
- Dc → dc
  - Regulators
  - Converters (dc → ac → dc)

Power systems

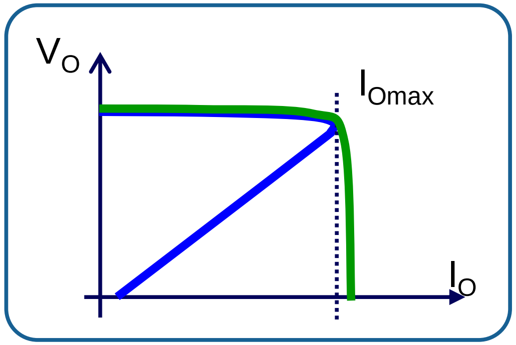
- Specifications
  - Input voltage/current, type, ...
  - Output voltage and current (maximum ranges allowed)
  - Adjustment, stability, performance, …
  - Special needs (precision, fail-safe, ...)
- Functional units
  - Input protections
  - Galvanic isolation (if required)
  - Ac-dc conversion (may have a filter)
  - Regulator
  - Output protection

Input parameters

- Type
  - Ac, dc, battery, dynamo, solar panel, ...
- Nominal value and range
  - 100–240 Vac, 12 Vdc ± 10 %, ...
- Frequency (if ac)
  - 50 Hz, 45–65 Hz, 400 Hz, ...
- Noise and spurious
  - Harmonics
  - Transients
  - ...

Output parameters

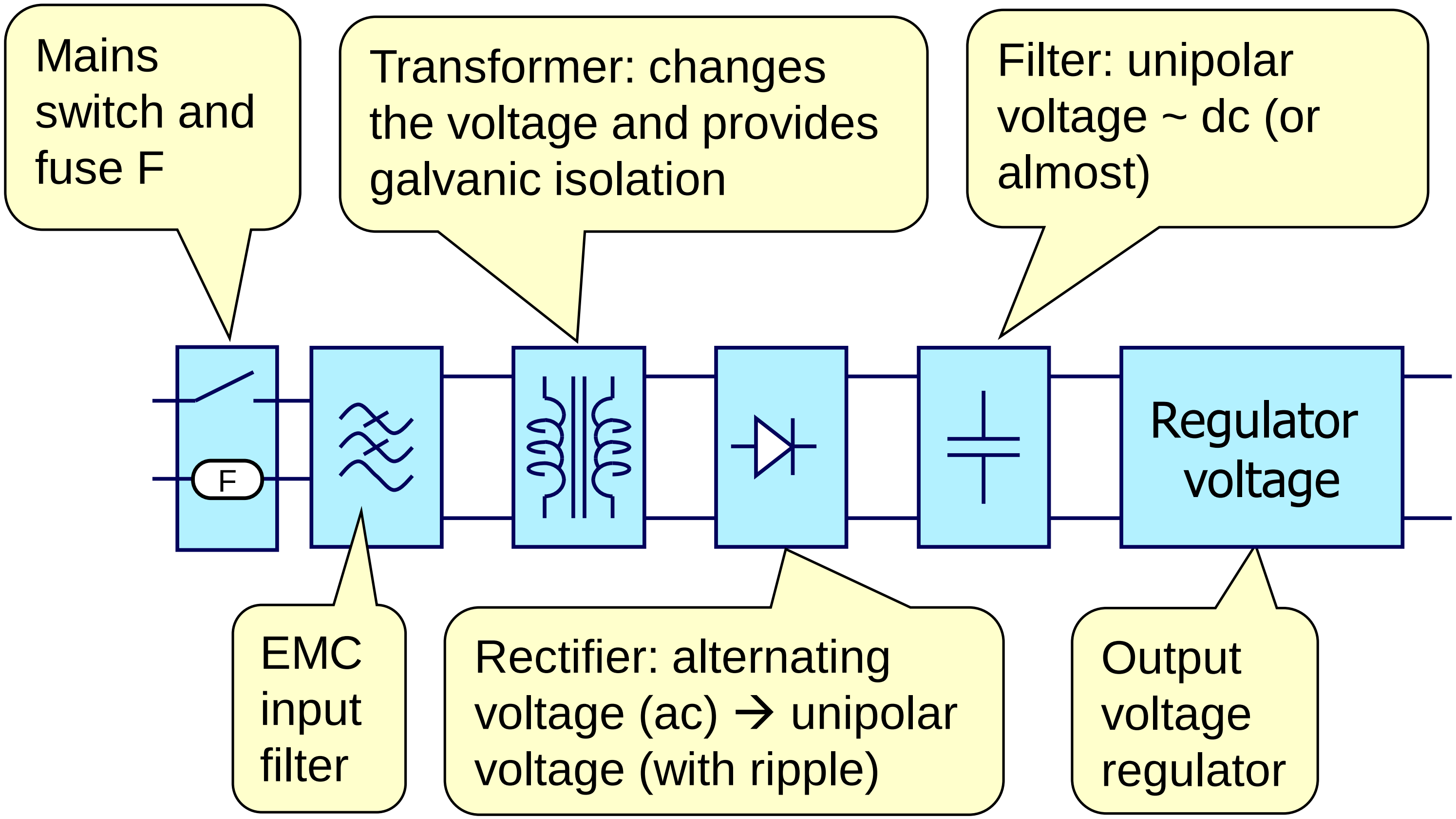
- Nominal values (are on label) and tolerances
  - Output voltage V_O: 12 V, 5 V ± 10 %, …
  - Current I_O (min, max, ...): 0.1 A, 0–50 A, ...
  - Ripple (periodic changes) and noise (random changes)
- Stability
  - Stabilization as the load varies: $R_O = \Delta V_O / \Delta I_O$
  - Stabilization for input variations (line): $S_V = \Delta V_O / \Delta V_I$
- Other parameters
  - Foldback, fail safe, protections, ...
  - Temperature: max, min, derating, ...
  - Early power-off signal



Safety and protections

- Prevent damage other parts of the system
  - User (safety) — No electric shock! → galvanic isolation
  - Load — Avoid output overvoltage
  - Input source (mains or battery) — Input current limiter (fuse)
  - EMC — Do not generate external noise
  - Fail-safe — Do no harm in case of failure
- Power system protection
  - Output current limiter (in case of faults or shorts)
  - Protect from input overvoltage
  - Temperature (ambient and heat dissipation)
  - ...

Block diagram of “classic” PSU



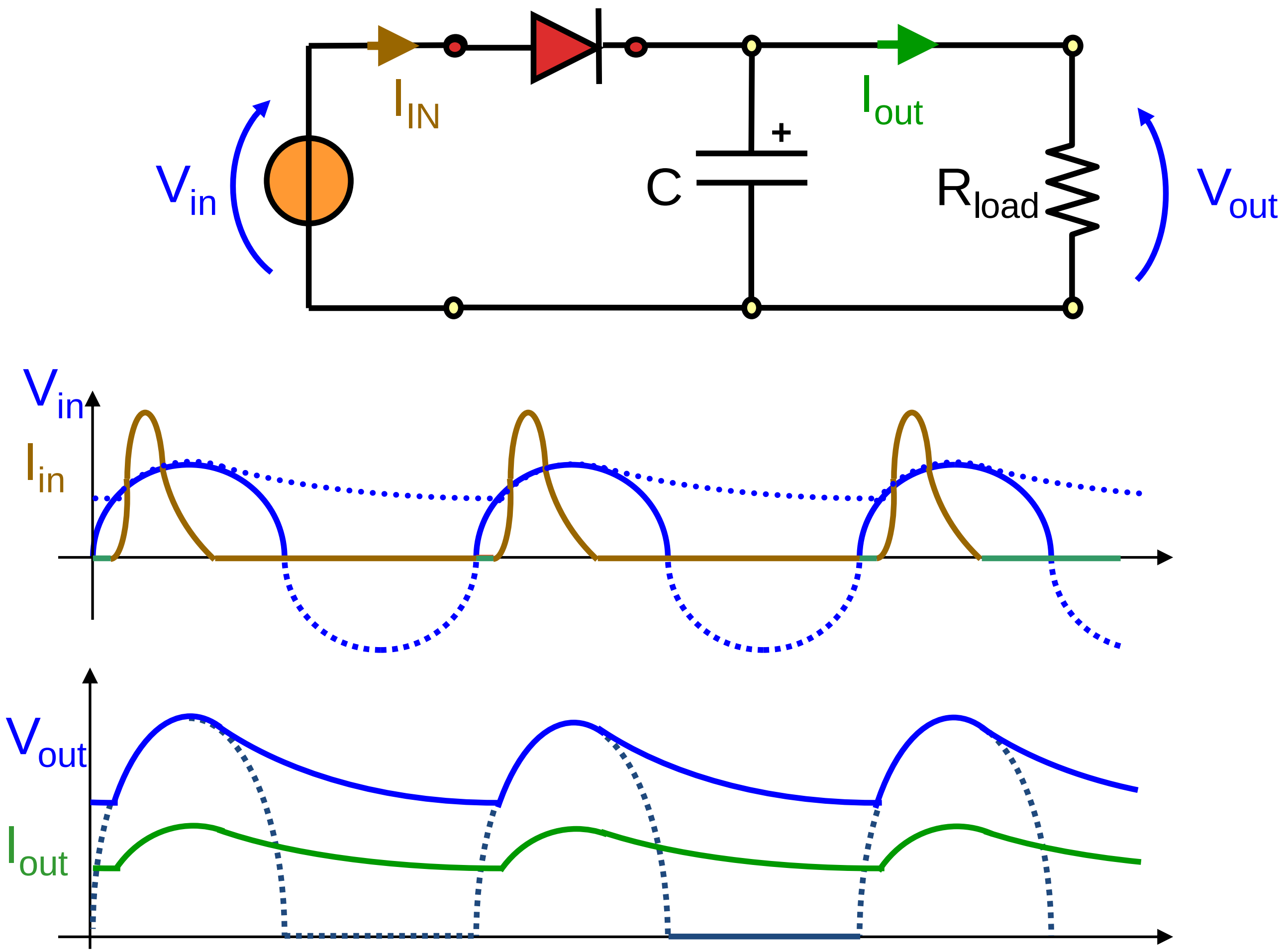
Input loop

- The mains ON/OFF switch isolate the supply
  - Not always present; often OFF is a standby
- Input filter
  - Blocks conducted interferences
  - Passive filter
- Fuse: disconnects excessive currents, fault protection
- Transformer
  - Brings the voltage to desired value, with good yield (η)
  - Guarantees galvanic isolation – safety!
  - Big, heavy, expensive, ...
    - Move to switching power supplies

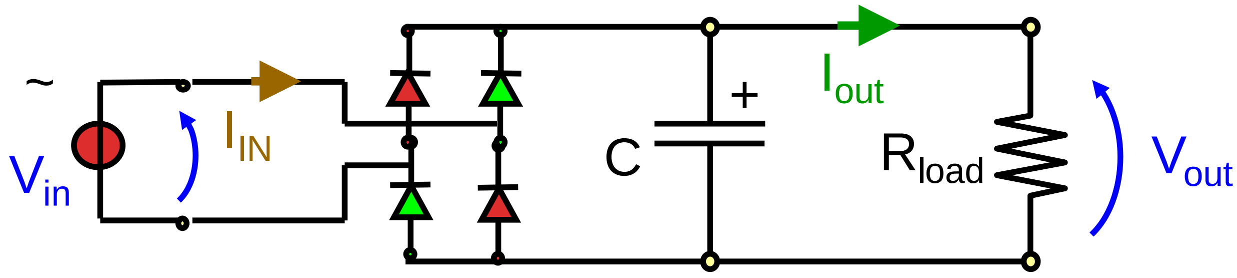
Ac–dc conversion

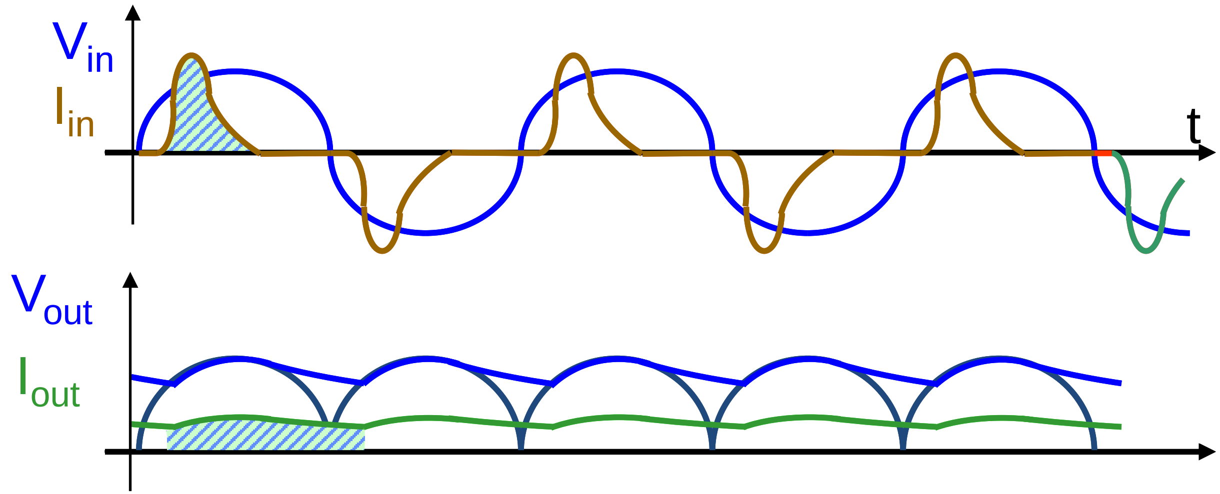
- Ac–dc conversion requires two basic elements
- Rectifier
  - Transforms bipolar ac voltage into unipolar voltage
  - Use standard diodes (or controlled diodes for high power)
  - The rectified voltage has a dc component and many ac components (harmonics of the mains ac)
- Hum filter
  - Transfers the dc component without attenuation
  - Removes or reduces the ac components
  - Passive circuit: low-pass filter RC, LC

Half-wave rectifier



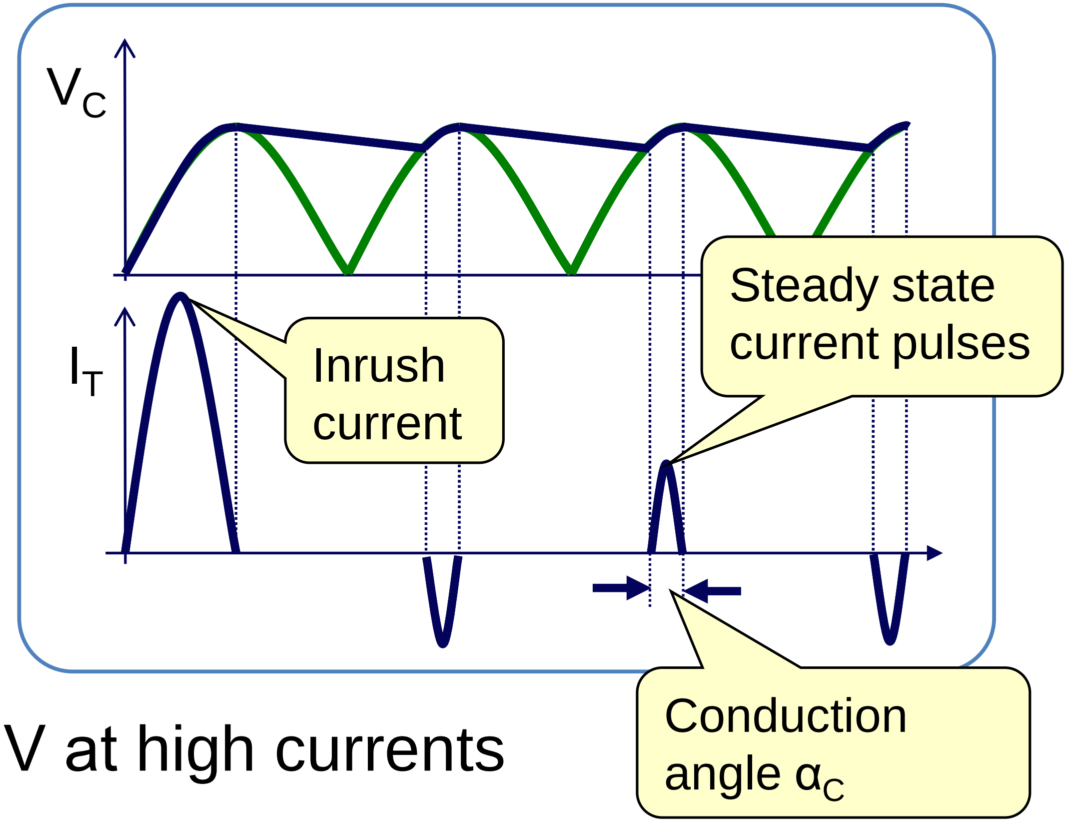
Full-wave rectifier





Current flow

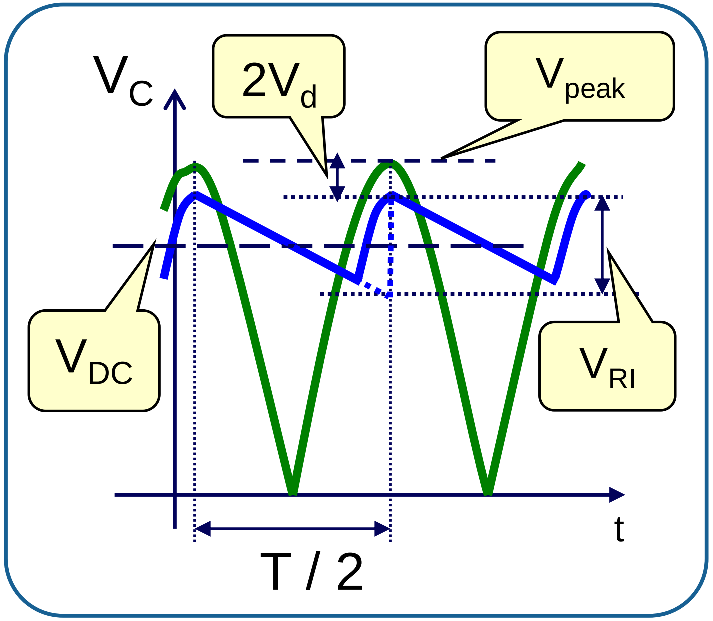
- First cycle
  - ♦ Fully charge the filter capacitor
  - ♦ High current, ”inrush”
- Steady state
  - ♦ Peak current much higher than the output average current (≈ x5 if the diode conducts 20 % of the time)
  - ♦ Voltage drop on diodes ≈ 1 V at high currents
  - ♦ Non-sinusoidal current
    - Harmonics, noise emission



Output ripple

- Simplifying hypotheses
  - Linear C discharge, i.e., constant load current
  - Sawtooth ripple, i.e., C fully charges at
    - Half-wave rectifier: K · T
    - Full-wave rectifier: K · T/2
- Full-wave rectifier ripple voltage
  - $V_{RI} = (I_O\ T/2) / C = I_O / (2\ f\ C)$
  - Half-wave rectifier: T instead of T/2
- Output voltage V_{DC}
  - $V_{DC} = V_{peak} – V_{RI} / 2$
  - With a Vd drop on the diode

    $V_{DC} = V_{peak} – 2\ Vd – V_{RI} / 2$

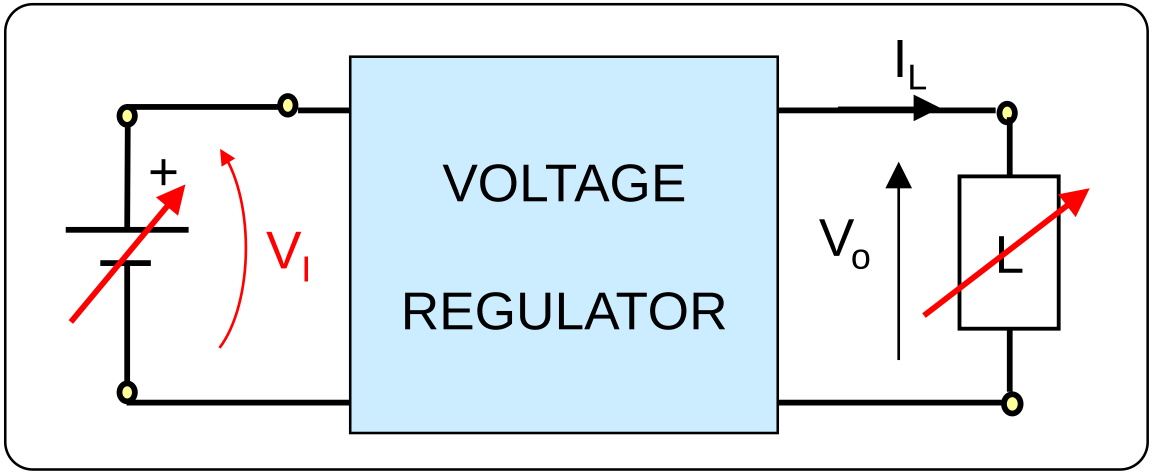


Disadvantages of the “classic” structure

- Transformer works at mains frequency (50/60 Hz)
  - ♦ Bulky, heavy, expensive
- For low ripple
  - ♦ Large filter capacitors → bulky and expensive
  - ♦ Strong impulsive currents → diode losses, interferences (EMI)
    - Forbidden by EC rules for powers > 10 W
- Alternative structures
  - ♦ Active regulators to reduce the ripple
  - ♦ Switching Power Supplies
    - Move the transformer to high frequencies
    - High efficiency, small size
    - Mandatory by EC rules for P > 10 W

Output voltage regulator

- The voltage regulator supplies constant V_O
  - ♦ Stabilization for load variations $S_L = \Delta V_O / \Delta I_L$
    - Equivalent output resistance $R_O = S_L$
  - ♦ Stabilization for input voltage V_I variations
    - Input / output regulation $S_I = \Delta V_O / \Delta V_I$
    - Reduction of ripple (seen as a V_I change)

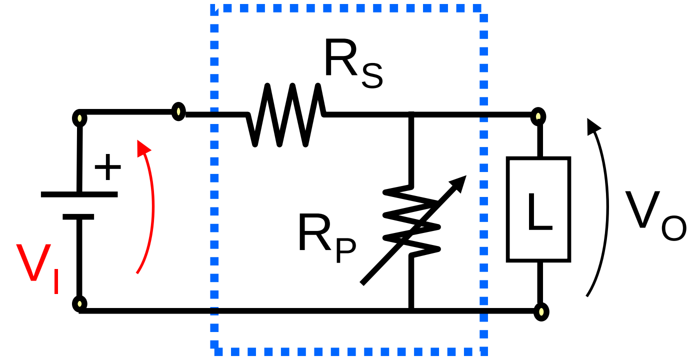


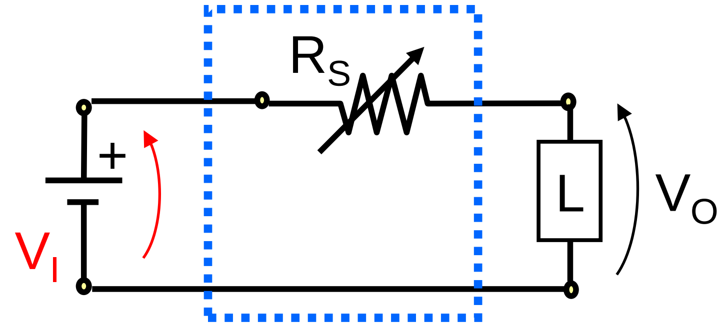
Active (linear) regulator

- Parallel regulators (shunt)
  - Zener diode
  - Voltage references
- Series regulators
  - Circuits with transistors and operational amplifiers
  - Can limit the current
- Integrated regulators
  - Standard
  - 3-terminals
  - Low-DropOut (LDO)

Series and parallel regulators

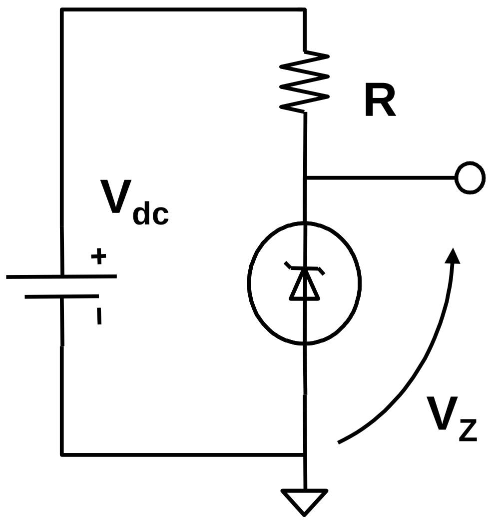
- Objective
  - ♦ V_O constant for variations of V_I, L
- Two basic techniques
  - ♦ *Current* divider
    - Change the split ratio acting on the parallel branch R_P
    - Parallel regulator
  - ♦ *Voltage* divider
    - Change the ratio by acting on the series branch R_S
    - Series regulator





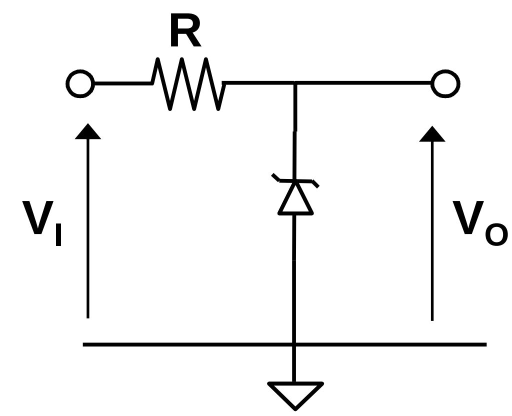
Parallel regulator (Zener diode)

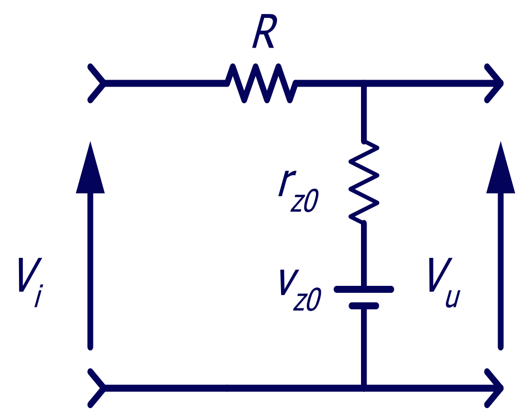
- Basic parallel controller: Zener diode
  - Very simple
  - Low efficiency, suitable for low power
  - Voltage references are parallel regulators (low current)
- Currents in Zener diodes
  - Higher than I_{Zmin} (~5 mA)
  - Lower than I_{Zmax}
    - To limit the dissipated power



Exercise E2.1: Zener regulator

- Design a parallel regulator with
  - V_I = 10 V → 20 V
  - V_O = 5 V (as close as possible)
  - I_O = 0 mA → 100 mA
- Available Zener diode
  - V_{ZO} = 5 V, R_Z = 1 Ω, I_{Zmin} = 5 mA
  - P_{Zmax} = 2 W
- Calculate
  - Drop resistance R (min/max)
  - V_O min/max (various combinations of V_I, I_O, R)
  - P_{Rmax} for R

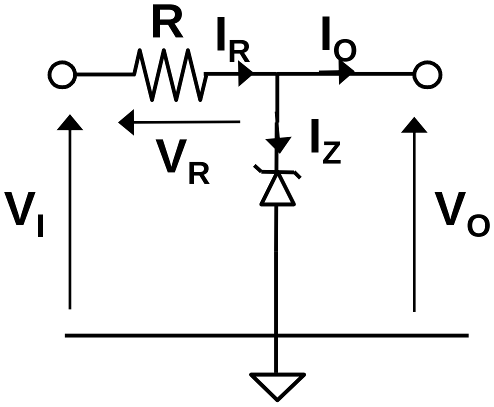




Exercise E2.1: Zener regulator: R_{min}

$$V_I = V_R + V_O = R\, I_R + V_O = R(I_O + I_Z) + V_O$$

$$R = \frac{V_I - V_O}{I_O + I_Z}$$



The minimum R value should limit the power dissipation on the Zener diode when through it flows the maximum current, i.e.:

V_{Imax} = 20 V, I_{Omin} = 0 A

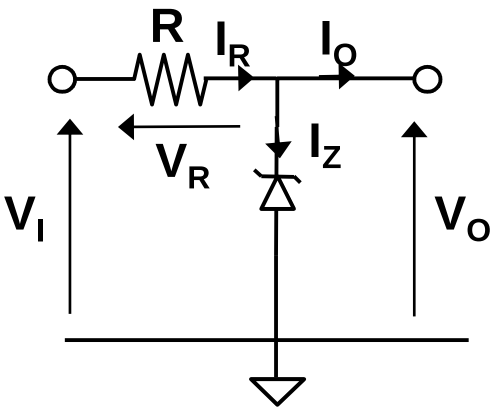
$I_{Zmax} = P_{Zmax} / V_{ZO}$ = 2 W / 5 V = 400 mA

$$R_{\min} = \frac{20\ \mathrm{V} - 5\ \mathrm{V}}{0\ \mathrm{A} + 0.4\ \mathrm{A}} = 37.5\ \Omega$$

Exercise E2.1: Zener regulator: R_{max}

$$V_I = V_R + V_O = R\,I_R + V_O = R(I_O + I_Z) + V_O$$

$$R = \frac{V_I - V_O}{I_O + I_Z}$$



The voltage drop on the maximum R should allow the Zener diode to regulate (i.e., $I_Z \geq I_{Zmin}$) when V_I is minimum and output (load) current I_O is maximum

V_{Imin} = 10 V, I_{Omax} = 100 mA, I_{Zmin} = 5 mA

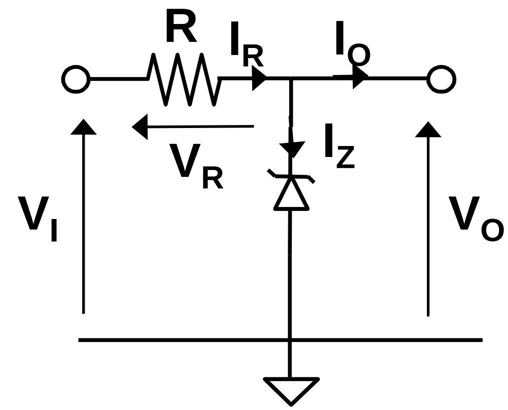
$$R_{\max} = \frac{10\ \mathrm{V} - 5\ \mathrm{V}}{0.1\ \mathrm{A} + 0.005\ \mathrm{A}} = 47.62\ \Omega$$

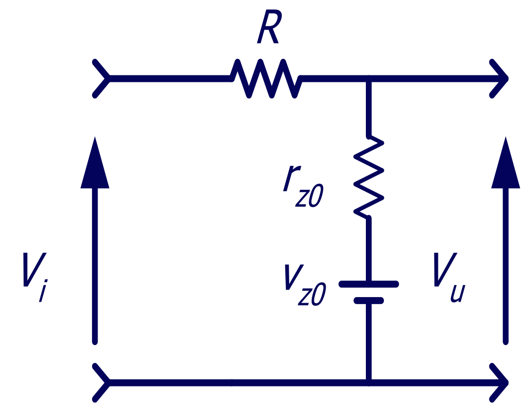
Exercise E2.1: Zener regulator: $V_{Omin/max}$

$$V_O = I_Z\ R_Z + V_Z$$

$$V_{O\min} = I_{Z\min}\ R_Z + V_Z$$
$$V_{O\min} = 5\ \mathrm{mA}\ \cdot 1\ \Omega + 5\ \mathrm{V} = 5.005\ \mathrm{V}$$

$$V_{O\max} = I_{Z\max}\ R_Z + V_Z$$
$$I_{Z\max} = \frac{P_{Z\max}}{V_Z} = \frac{2\ \mathrm{W}}{5\ \mathrm{V}} = 0.4\ \mathrm{A}$$
$$V_{O\max} = 0.4\ \mathrm{A}\ \cdot 1\ \Omega + 5\ \mathrm{V} = 5.4\ \mathrm{V}$$





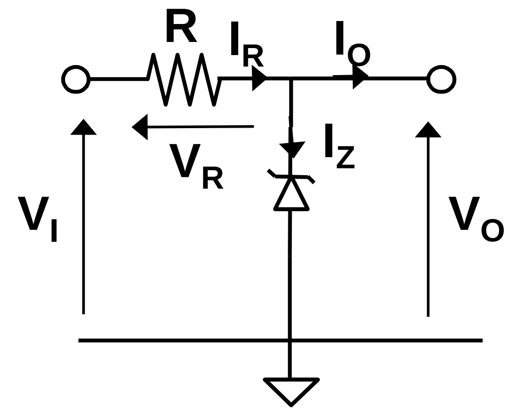
Exercise E2.1: Zener regulator: P_{Rmax}

The power dissipated in R

$$P_R = \frac{V_R^2}{R}$$

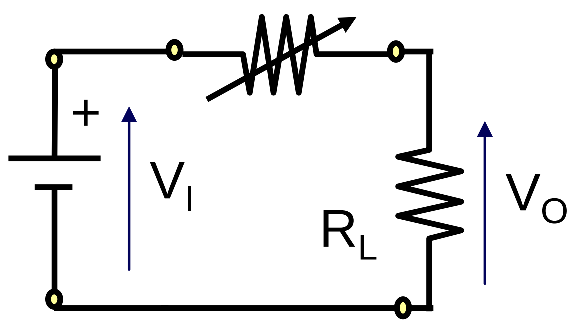
Maximum dissipated power in R
is for maximum V_R and minimum R

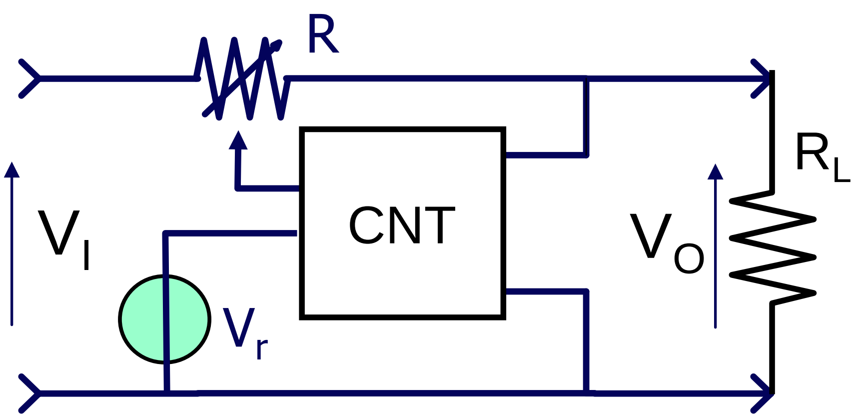
$$P_{R\max} = \frac{V_{R\max}^2}{R_{\min}} = \frac{(20\ \mathrm{V}\ - 5\ \mathrm{V})^2}{37.5\ \Omega} = 6\ \mathrm{W}$$



Series regulator – basic schematic

- The series regulator acts as a variable resistor to reduce power consumption
  - The variable resistor is a BJT or MOS
  - The CNT controller compares the V_O output with a reference V_r





Series Regulators

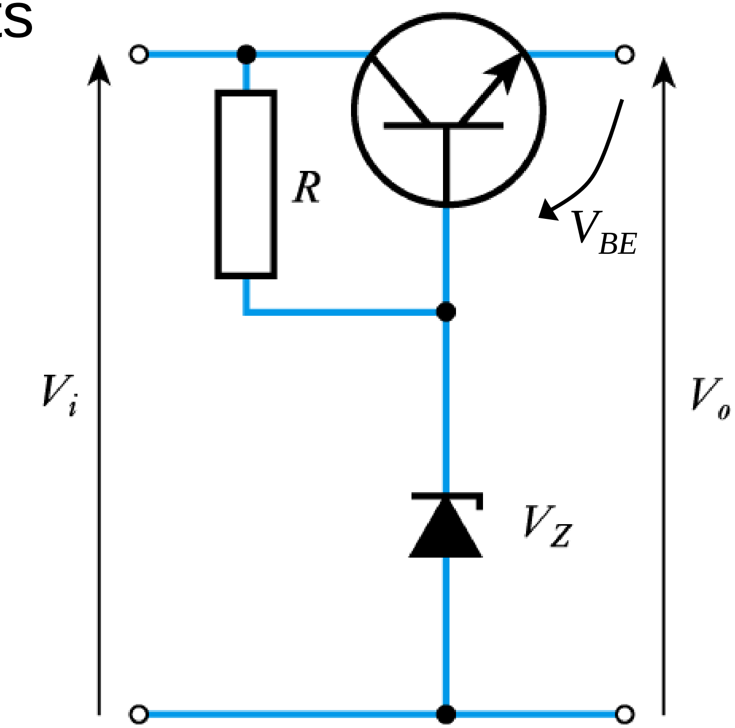
- Require a controlled “variable resistor”
  - Can use BJT or MOS
  - Current amplifier controlled by the voltage reference
  - Implemented with voltage reference and op-amp
- Always $V_O < V_I$
  - All regulators require a minimum voltage drop (V_{drop})
    - Losses, reduces efficiency
  - Low Drop Out (LDO) low drop / high efficiency regulators
- Available as standard integrated circuits (commodity)
  - Fixed voltage (5 V, 6 V, 9 V, 12 V, ...)
  - Variable voltage

Example of series regulator

- Resistance-Zener base regulator
  - Regulates by splitting the current between the Zener and load
  - Low efficiency, can manage low currents
- V_Z and current amplifier with emitter follower (CC)
  - Output voltage

    $V_O = V_Z – V_{BE} \rightarrow$ same S_I of the Zener
  - Load current can vary widely

    $\Delta I_O = \Delta I_Z\, \beta \rightarrow$ lower R_O (S_L)

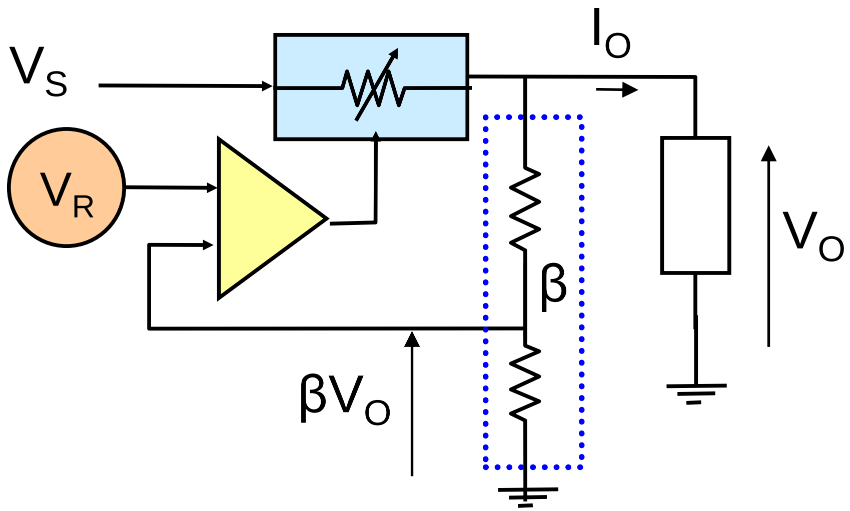


Reaction regulator

- Reference generator and amplifier
  - Compare a fraction β of the output voltage V_O with the reference voltage V_R
- Drive the control element to keep

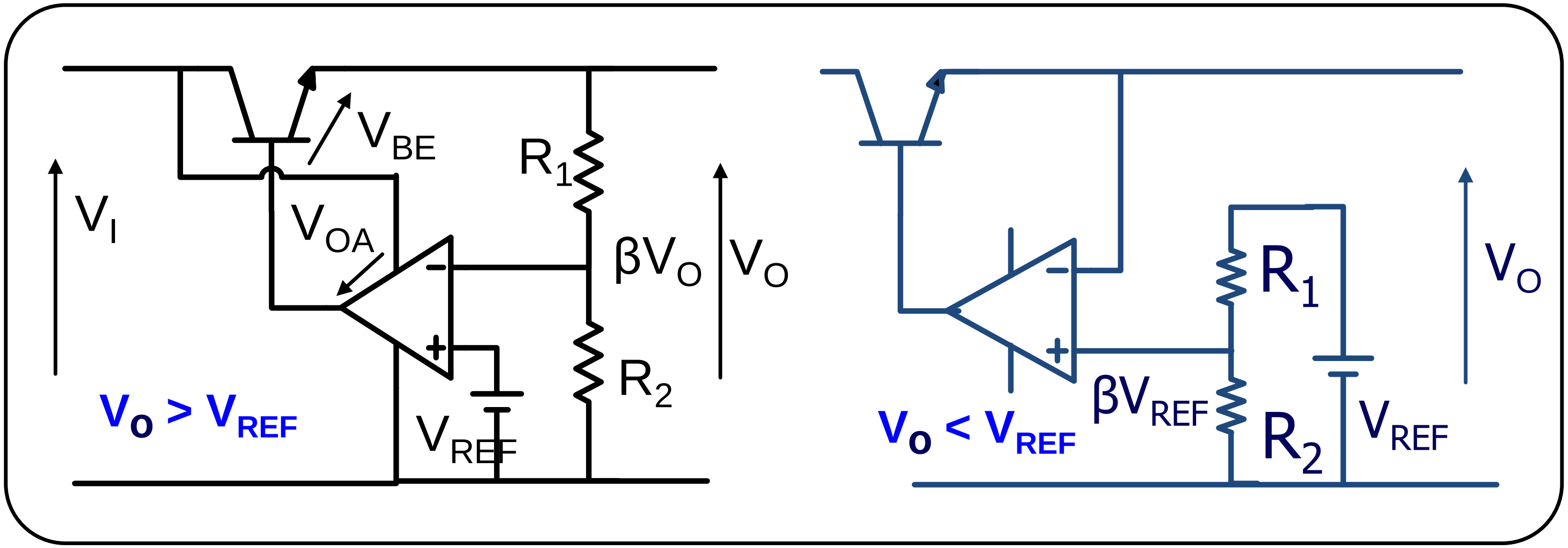
$\beta V_O = V_R$

- We need a voltage reference (V_R, generated with a Zener diode or other means)



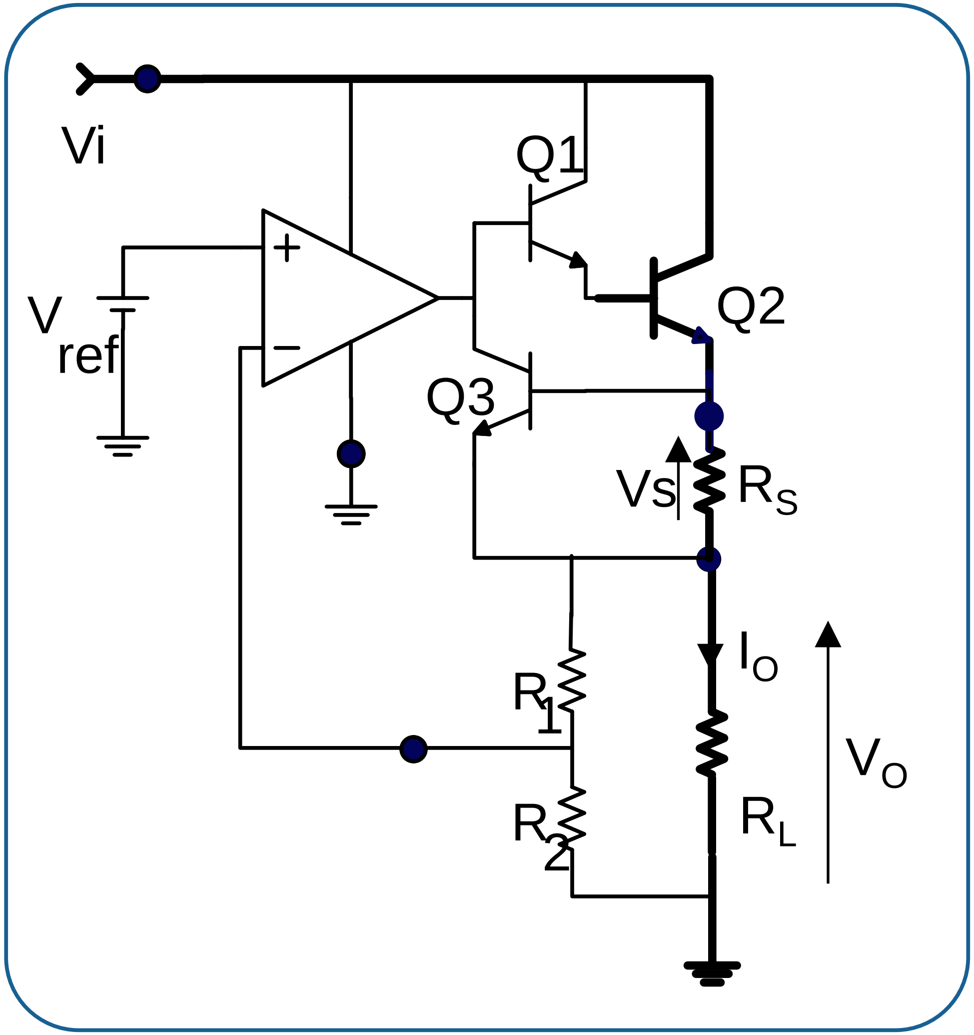
Regulator with op-amp and BJT

- BJT used as Common Collector power stage
  - If $V_O > V_{REF}$ → $\beta V_O = V_{REF}$
  - If $V_O < V_{REF}$ → $V_O = \beta V_{REF}$
  - Voltage drop from V_I to V_O is V_{OA} (within the op-amp) + V_{BE}



Current limiter

- Power transistors Q1 + Q2 (Darlington configuration)
- Current sense: R_S
  - If V_S exceeds 0.7 V, Q3 draws current from Q1 base
  - Reduced current in Q1 and Q2
- $I_{Omax} = 0.7 / R_S$



Efficiency of series regulators

- Losses from voltage drops and "leakage" currents, I_{LEAK} (or quiescent currents, I_Q)
  - Includes the supply of the op-amp, the Zener diode, etc.
  - Normally, $I_{LEAK} << I_{OUT}$

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} \times (I_{IN} - I_{LEAK})}{V_{IN} \times I_{IN}} \cong \frac{V_{OUT}}{V_{IN}}$$

- To improve performance
  - Reduce voltage drop → regulators Low-DropOut (LDO)
  - Reduce leakage currents, I_{LEAK} → low power ref. voltage, V_R
  - Use switching regulators

Commercial voltage regulators

- Are available many integrated regulators
- Linear regulators: 78xx family (positive voltages)
  - XX = output voltage
  - High power cases
  - Max current depends on package and heatsink
    - 50 mA … 5 A
- Other devices
  - 79xx family: negative voltages
  - 317 Family: variable output voltages
  - LM9076: LDO
  - ….

78xx data sheet

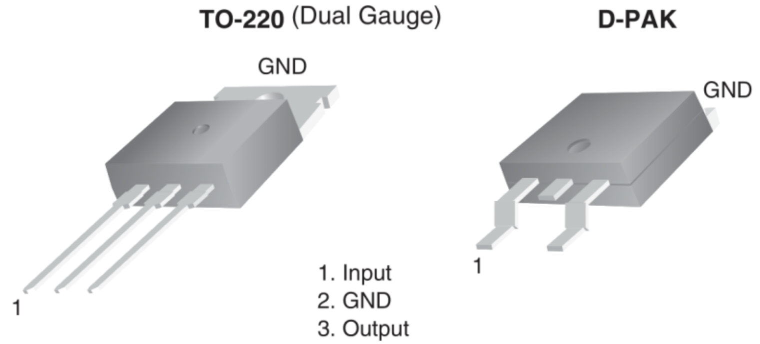
KA78XXE / KA78XXAE
3-Terminal 1 A Positive Voltage Regulator

Features

- Output Current up to 1 A
- Output Voltages of 5, 6, 8, 9, 10, 12, 15, 18, 24 V
- Thermal Overload Protection
- Short-Circuit Protection
- Output Transistor Safe Operating Area Protection

Description

The KA78XXE / KA78XXAE series of three-terminal positive regulators is available in the TO-220 / D-PAK package with several fixed-output voltages, making them useful in a wide range of applications. Each type employs internal current limiting, thermal shut-down, and safe operating area. If adequate heat sinking is provided, they can deliver over 1 A output current. Although designed primarily as fixed-voltage regulators, these devices can be used with external components for adjustable voltages and currents.



Electrical Characteristics (KA7805E / KA7805ER)

Refer to test circuit, -40°C < T_J < 125°C, I_O = 500 mA, V_I =10 V, C_I= 0.33 µF, C_O=0.1 µF, unless otherwise specified.

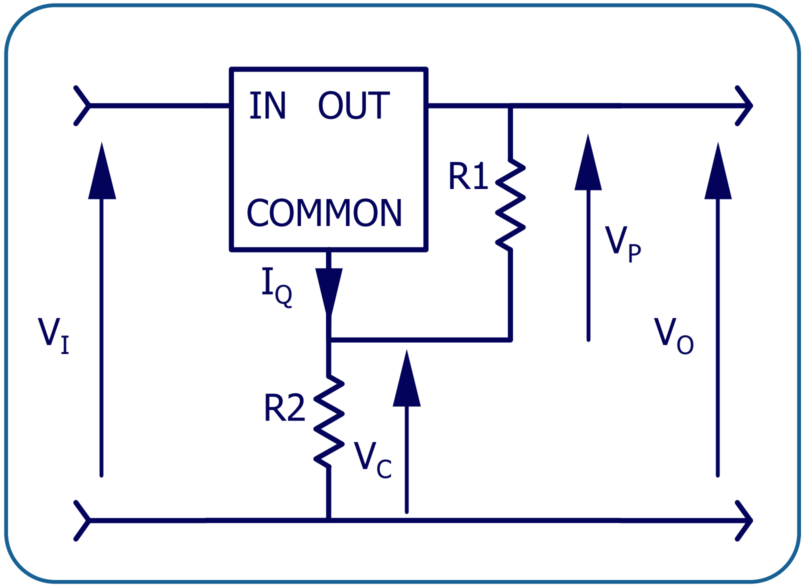
Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
V_O	Output Voltage	T_J = +25°C	4.80	5.00	5.20	V
		5.0 mA I_O 1.0 A, P_O 15 W, V_I = 7 V to 20 V	4.75	5.00	5.25	
Regline	Line Regulation(3)	T_J = +25°C, V_I = 7 V to 25 V		4.0	100.0	mV
		V_I = 8 V to 12 V		1.6	50.0	
Regload	Load Regulation(3)	T_J = +25°C, I_O = 5.0 mA to 1.5 A		9	100	mV
		I_O = 250 mA to 750 mA		4	50	
I_Q	Quiescent Current	T_J = +25°C		5	8	mA
ΔI_Q	Quiescent Current Change	I_O = 5 mA to 1.0 A		0.03	0.50	mA
		V_I = 7 V to 25 V		0.30	1.30	
$\Delta V_O/\Delta T$	Output Voltage Drift(4)	I_O = 5 mA		-0.8		mV/°C
V_N	Output Noise Voltage	f = 10 Hz to 100 kHz, T_A = +25°C		42		µV
RR	Ripple Rejection(4)	f = 120 Hz, V_I = 8 V to 18 V	62	73		dB
V_{Drop}	Dropout Voltage	I_O = 1 A, T_J = +25°C		2		V
R_O	Output Resistance(4)	f = 1 kHz		15		mΩ
I_{SC}	Short-Circuit Current	V_I = 35 V, T_A = +25°C		230		mA
I_{PK}	Peak Current(4)	T_J = +25°C		2.2		A

Notes:

3. Load and line regulation are specified at constant junction temperature. Changes in V_O due to heating effects must be taken into account separately. Pulse testing with low duty is used.
4. These parameters, although guaranteed, are not 100% tested in production.

Variable voltages with 3-pin regulators

- 3-pin regulators maintain a predetermined voltage V_P between the OUT and COMMON pins
  - We ignore the quiescent current I_Q
  - $V_P = V_O\, R1 / (R1 + R2)$
  - $V_O = V_P\, (R1 + R2) / R1$
- Replacing $I_Q\, R2$ with its Thevenin equivalent, we add $I_Q\, R2$ to the output loop
  - $V_O = V_P\, (R1 + R2) / R1 + I_Q\, R2$



Exercise E2.2: voltage regulator design

- Specifications: PSU with linear regulator for 5 V, 1 A load
  - Draw the block diagram with and without regulator
  - Define the characteristics of the transformer, diodes, capacitor
  - Evaluate S_V (stabilization) and R_O (output resistance)
- Add a Zener diode regulator
  - Define the Zener diode parameters
  - Evaluate the new S_V and R_O
- Add a power transistor (CC)
  - Evaluate the new S_V and R_O
- Find (from catalog) a suitable 3-pin regulator
  - Compare the S_V and R_O with the previous results

Lecture E2 – final check

- What parameters define the characteristics of a regulator?
- Draw the block diagram of a power supply with regulator, describing the functions of each module.
- Plot the waveforms of voltages and currents for a double half-wave (loaded) rectifier.
- Describe how to calculate and measure the output ripple of an unstabilized power supply.
- Describe the differences between parallel and series regulators.
- What are the benefits of feedback voltage regulators?
- Explain how to obtain from a three-terminal (fixed voltage) regulator a different voltage than the one set.