MŰEGYETEM 1782
Budapest University of Technology and Economics
Department of Electron Devices

Technology of IT Devices

Lecture 11

Power supply

Contents

- Power supply
- AC/DC conversion
- Rectification
- DC/DC conversion
- Voltage references
- Power supplies

Electrical grid

- This is an interconnected network for delivering electricity from suppliers to consumers
- It consists of
  - **Generating stations** that produce electrical power
  - **High-voltage transmission lines** that carry power from distant sources to demand centers
  - **Distribution lines** that connect individual customers
- Electric power is distributed as alternating current
  - AC voltage may be increased or decreased using a transformer
  - This allows the power to be transmitted through power lines efficiently at high voltage, which reduces the power lost as heat due to resistance of the wire, and transformed to a lower, safer, voltage for use.
  - The power losses P_L in a conductor are a product of the square of the current (I) and the resistance (R) of the conductor

$$P_L = I^2 R$$

Example: Power loss of a street with 100 houses at full load. P_{peak}/house is 32 amps × 230 volts = 7.36kW. 100 houses -> 736 kW. 1 km long and a diam. of 30mm wire:

3200 amps @ 230V P_{loss}: 243 kW

36 amps @ 20kV P_{loss}: 0.031 kW

Electrical grid

- The electric power distribution networks provide alternating voltage – in the EU its RMS value is 230 V and its frequency is 50 Hz.
  - The RMS (root mean square) value of a sinusoidal voltage is the DC voltage that yields the same power dissipation as the time-averaged power dissipation of the AC signal

$$V_{RMS} = \lim_{T\to\infty} \sqrt{\frac{1}{T}\int_0^T [V(t)]^2 d\mathrm{t}}$$

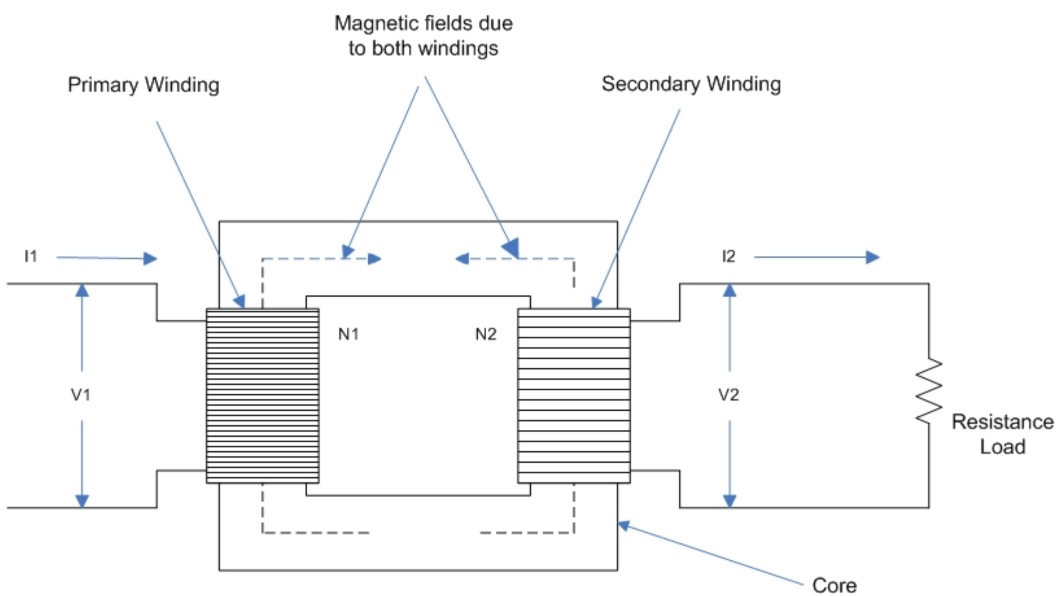
- Thus the function that describes the supply voltage is:
  - $\sqrt{2} \cdot 230 \sin(2\pi 50 t)$,
  - Amplitude is 325V
  - Frequency is 50Hz

Conversions

- From alternating current to alternating current (AC/AC)
  - Transformer
  - Increasing or decreasing the amplitude of the alternating current/voltage
- From alternating current to direct current (AC/DC)
  - Rectifier
- From direct current to direct current (DC/DC)
  - DC/DC converter or charge pump
  - Increasing or decreasing the voltage
- From direct current to alternating current (DC/AC)
  - Inverter
  - For example: UPS, PV cell systems, 3-phase synchronous or asynchronous electric motors in hybrid cars
  - Efficiency of conversion: $\eta = \frac{P_{OUT}}{P_{IN}}$
  - The goal is to achieve 100%!

Transformers

- A transformer is an electrical device that transfers energy between two or more circuits.
- The AC supply voltage is connected to the primary winding…
- ... and the load is connected to the secondary winding.
- In an ideal transformer $\frac{V_2}{V_1} = \frac{N_2}{N_1}$, where N is the number of turns
- Thus the ratio of the voltages at the two sides is equal to the ratio of the number of turns.



Transformers

- Ideally, the transformer is perfectly efficient: all incoming energy is transformed from the primary to the secondary circuit:

$$P_1 = V_1 \cdot I_1 = V_2 \cdot I_2 = P_2$$

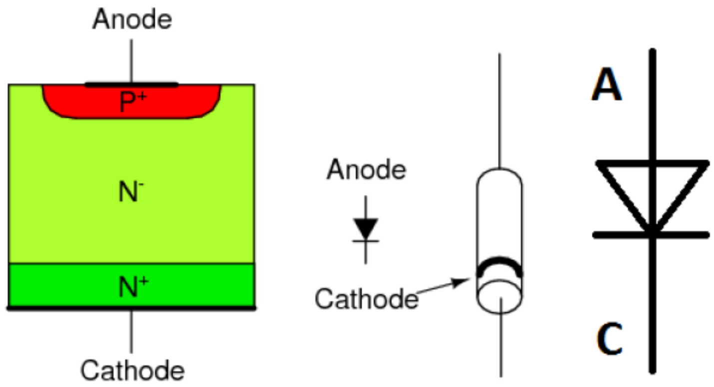
- but due to losses this is not true in a non-ideal case.
- Transformers are equally used to **step up** and to **step down** **alternating voltage.**

The first power transformer was made by Ottó Bláthy, Miksa Déri and Károly Zipernowsky at Ganz Works in 1885.

A modern, toroid transformer

Semiconductor diode

- A diode is a device that consists of one single pn-junction.



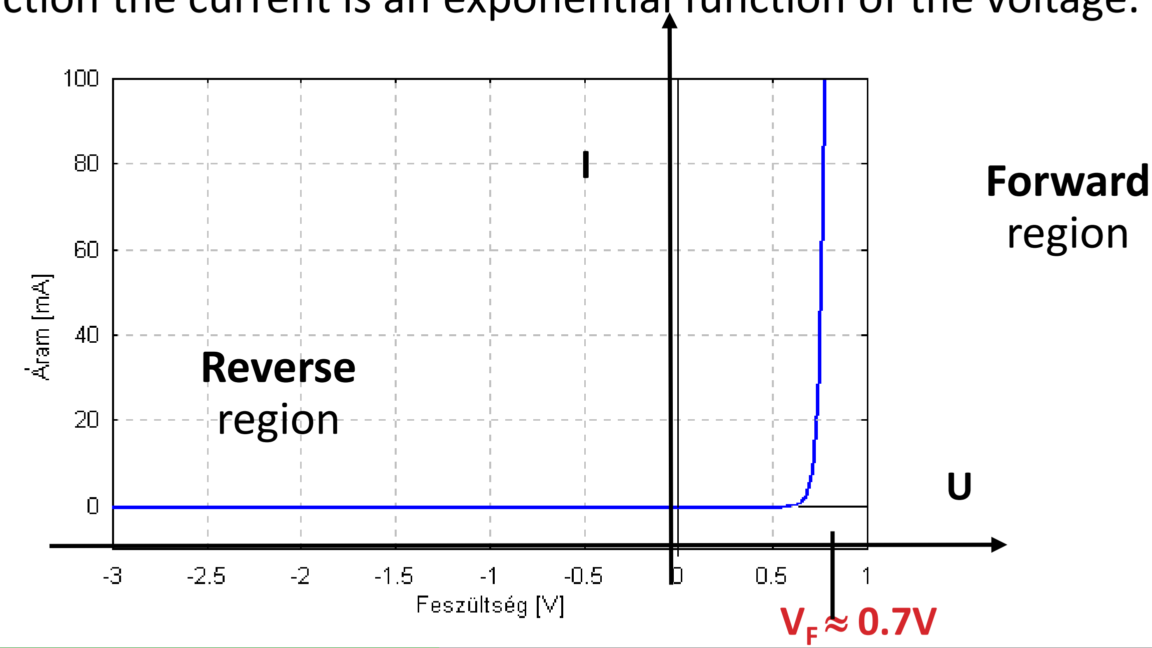
- The figure is distorted: the n-type layer is much shallower in reality.
- Forward direction: the p side is at a higher potential
- In the reverse direction its current is very low and is independent of the voltage: $I \sim 10^{-12}$ A/mm^2

Characteristic of a diode

- The current-voltage characteristic of the diode:

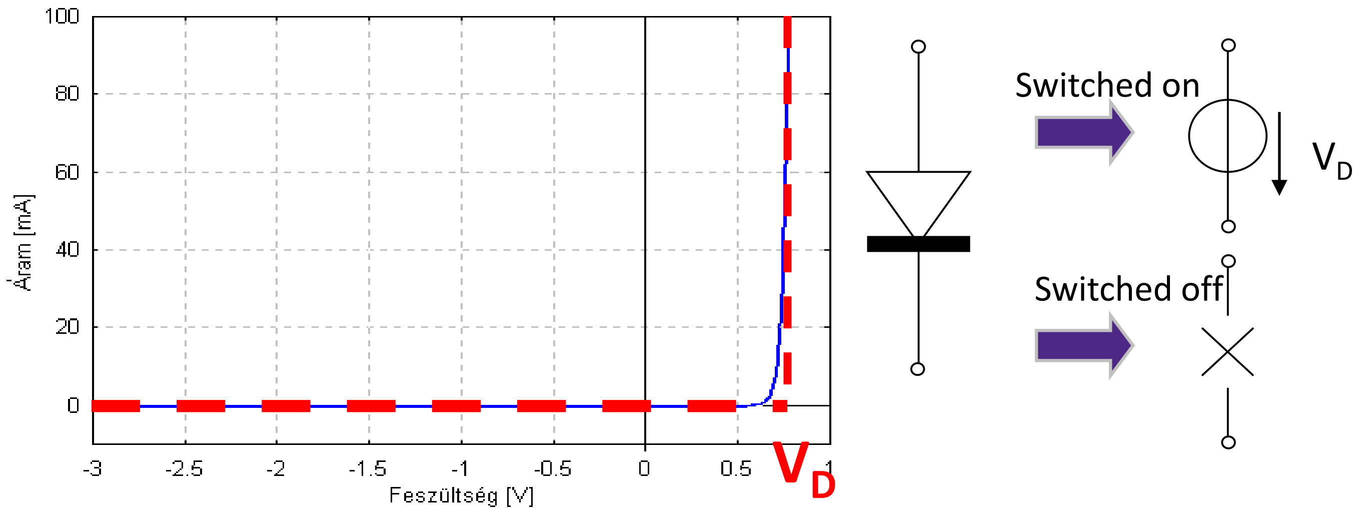
$$I = I_0\left(e^{\frac{V}{nV_T}} - 1\right)$$

  - I_o is the reverse current (saturation current) of the diode, depends only on the material constants and doping concentration
  - V_T is the thermal voltage (kT/q), 26mV at room temperature
  - n is the ideality factor (1-2)
  - In the forward direction the current is an exponential function of the voltage.

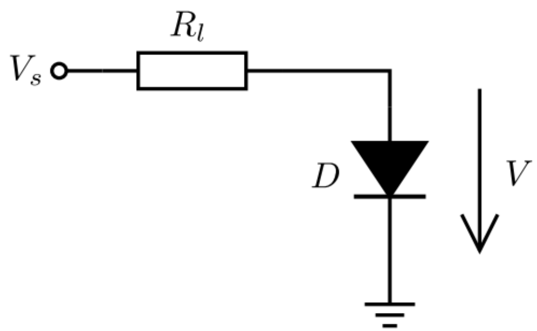


Semiconductor diode

- Example: What voltage increment causes 10x higher current?
  - $\frac{10I}{I} = \frac{I_0(e^{\frac{U+\Delta U}{U_T}} - 1)}{I_0(e^{\frac{U}{U_T}} - 1)} \approx e^{\frac{\Delta U}{U_T}}$
  - $\Delta U = U_T ln10 = 26mV \cdot 2.3 = 60mV$
- Due to the steep I-V characteristic we can substitute the diode with a 0.7V **voltage generator** in **forward region**, and an **open circuit** in **reverse region**.

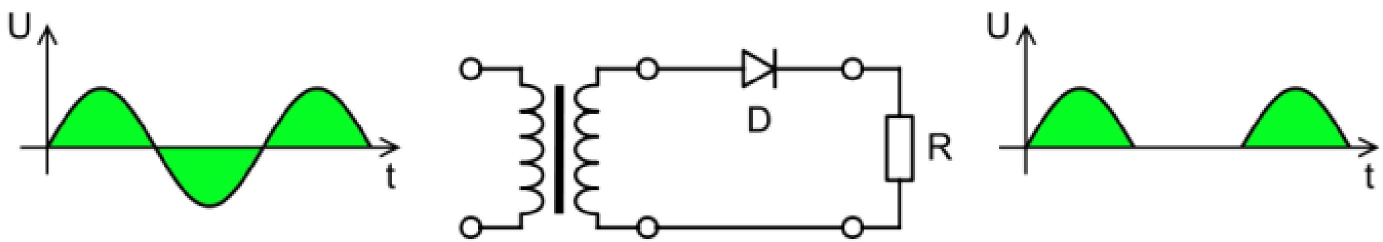


Example



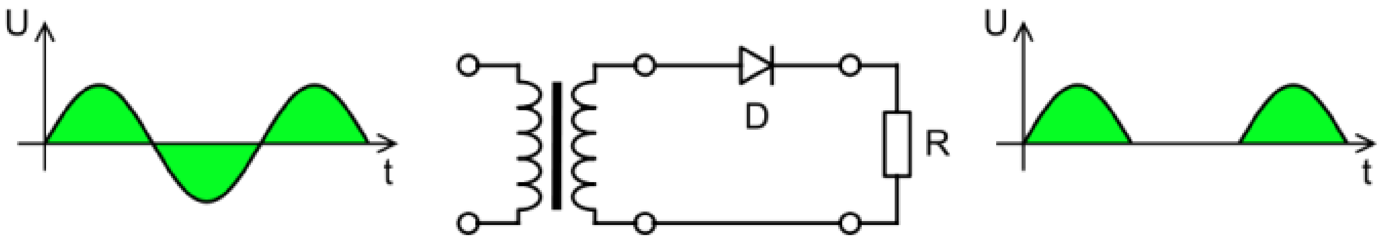
- Let's calculate the current of a diode!
- $I = \frac{U_t - U_D}{R_t}$
- If VS is 5V, resistance of the resistor is 1kΩ.
- The current is 4.3 mA using V_F = 0.7V approximation.
- Using a real diode (1N4148, I_0= 4.352nA, n=1.906)
  - The solution of $V_s = V + R_t I_0 \left(e^{\frac{V}{nV_T}} - 1\right)$ equation is
  - V=0.684V and I=4.316mA
- Thus the approximation is valid.

Half-wave rectification



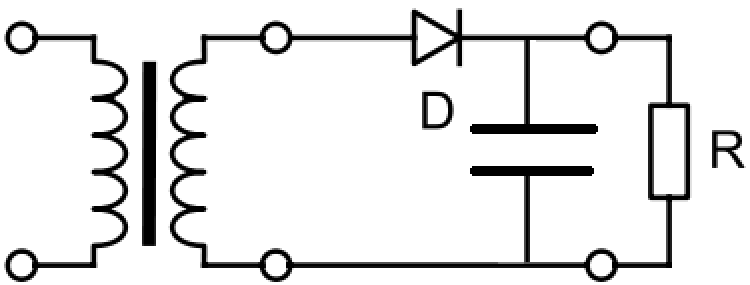
- The diode is open only when a forward voltage is applied on it, so current can flow in the circuit during the positive halves only.
- If the amplitude of the alternating voltage on the output of the transformer is V then
  - In forward direction the maximum voltage dropped on the resistor during the positive halves is $V_{max} = V - V_D$ (using the familiar diode approximation.)
  - The maximum current is $I_{max} = \frac{V - V_D}{R}$
  - During the negative halves the current is blocked by the diode so the maximum (reverse) voltage is V.
  - The break-down voltage of the diode has to be larger than *V*
  - Let V=16V, R=500Ω. Using a Si diode (V_D ~ 0.7V):
    - $V_{max} = 15.3V \;\; I_{max} = 30.6mA$

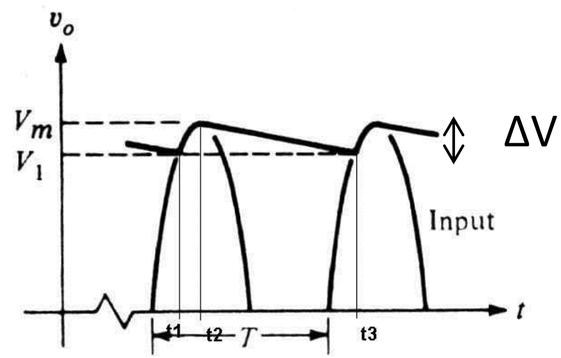
Half-wave rectification - problems



- Problems with half-wave rectification:
  - Only half of the input waveform reaches the output, thus the efficiency is low.
  - The output pulsates which makes it unsuitable for most applications.
  - It was used to charge batteries in the past.

Peak rectifier

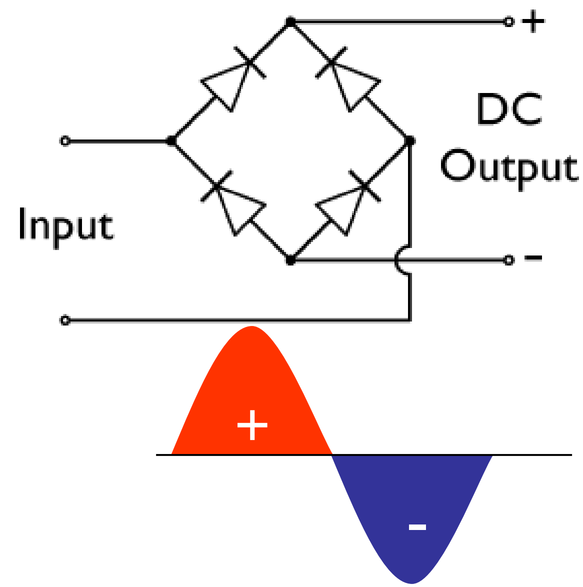


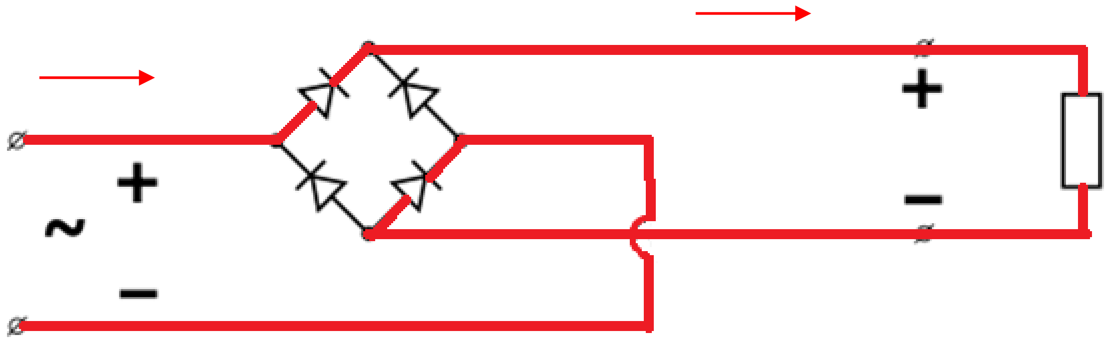


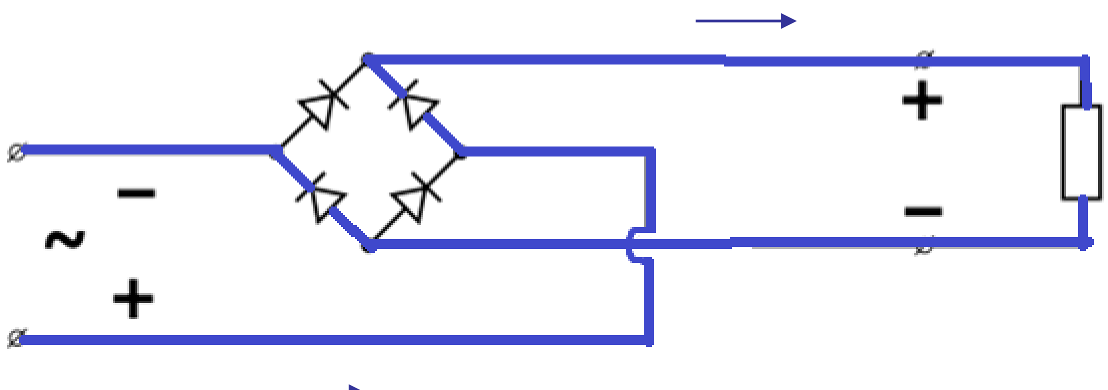
- A smoothing capacitor is added to the circuit.
- The capacitor is charged during the positive halves and is discharged gradually during the negative halves.
- At t_1: the voltage of the transformer is higher than that of the capacitor, thus the diode is open and the capacitor is charged to the peak value of the input signal
- At $t_{2:}$ the voltage of the input decreases below the voltage of the capacitor. The diode gets closed so in this phase the charge accumulated in the capacitor provides the current of R.
- Estimation of the output voltage fluctuation: $\Delta V = V_m - V_1$

Full-wave rectification / Grätz-bridge

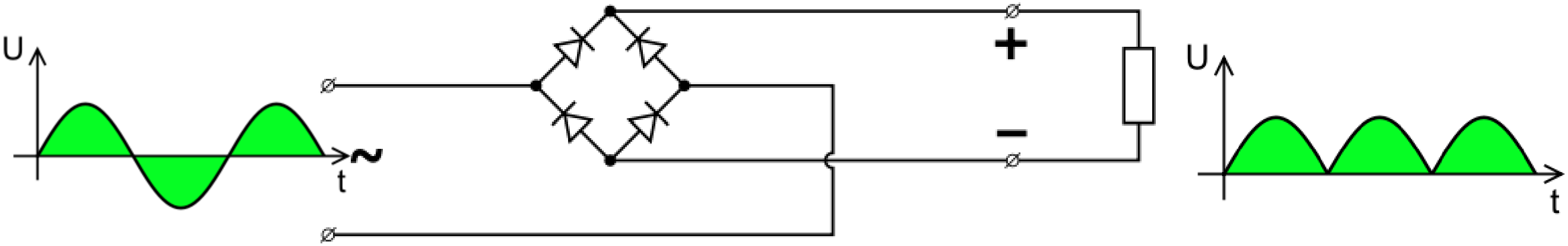
- It contains four diodes
- Grätz-bridges are sold in a package
- The red subcircuit is active during the positive half-wave
- The blue subcircuit is active during the negative half-wave.



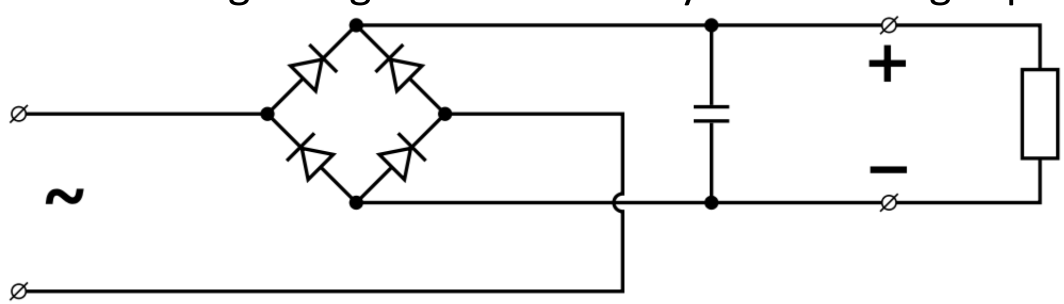




Full-wave rectification / Grätz-bridge

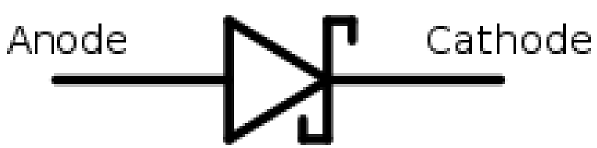


- The Grätz-bridge generates the absolute value of the input signal with a loss of $2 \cdot V_D$
- The amplitude of the input signal is V:
  - The maximum voltage of the resistor is $V_{max} = V - 2V_D$
  - The maximum current: $I_{max} = \frac{V-2V_D}{R}$
- During operation two diodes are opened and two diodes are closed.
- The voltage dropped on the closed diode pair is V , so the break-down voltage has to be larger than V/2.
- The fluctuation of the voltage is again decreased by a smoothing capacitor:



Loss reduction

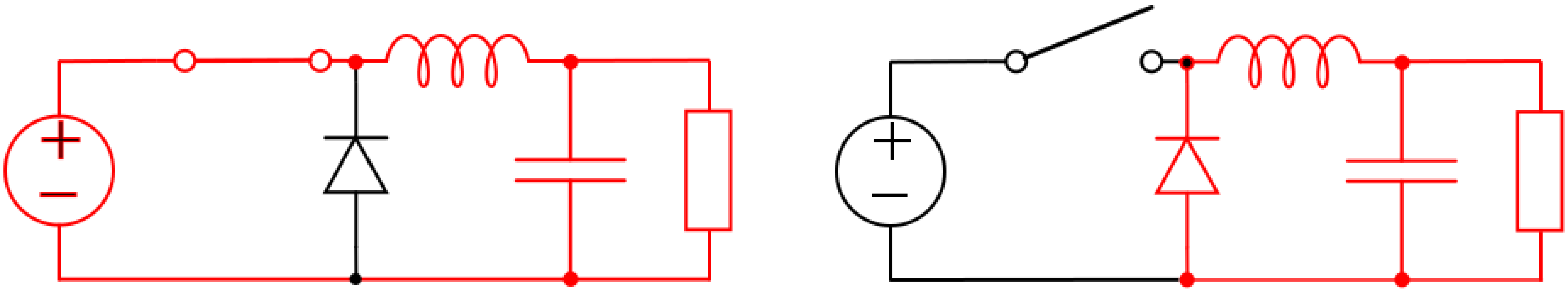
- At higher current the forward voltage drop on the diodes causes high power dissipation
  - Diodes become hot
- Schottky diode
  - It consists of a metal-semiconductor junction.
  - It has a low forward drop (around 0.2–0.4 V) and it also operates faster than Si diodes.
  - But the breakdown voltage is much lower!



DC/DC conversion

- A DC/DC converter accepts a DC input voltage and produces a DC output voltage
- The output produced is at a different voltage level than the input
- Power levels range from very low (small batteries) to very high (high-voltage power transmission)
  - Small size, high efficiency (> 90%)
  - Only a few electronic components required
  - Well controllable
- Main idea
  - Store the input energy temporarily and then release that energy to the output at a different voltage
  - The storage may be in either magnetic field storage components (inductors, transformers) or electric field storage components (capacitors).
  - The switching element is a MOS transistor

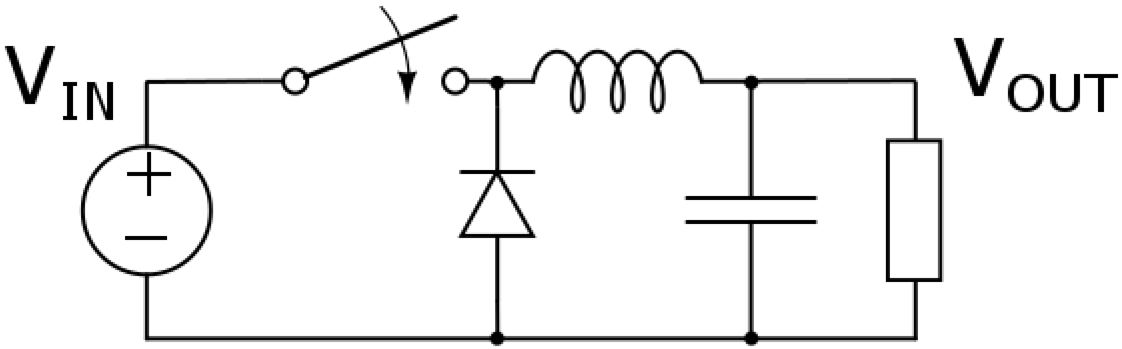
Buck / step down converter



- It steps down voltage (while stepping up current)
- It consists of a MOS transistor (as a switch), a coil, a diode, and a (smoothing) capacitor.
- The load is represented by the resistor
- They are used to in computers to convert the main (bulk) supply voltage (often 12V) down to lower voltages needed by USB, DRAM, the CPU (1.8V or less), etc.

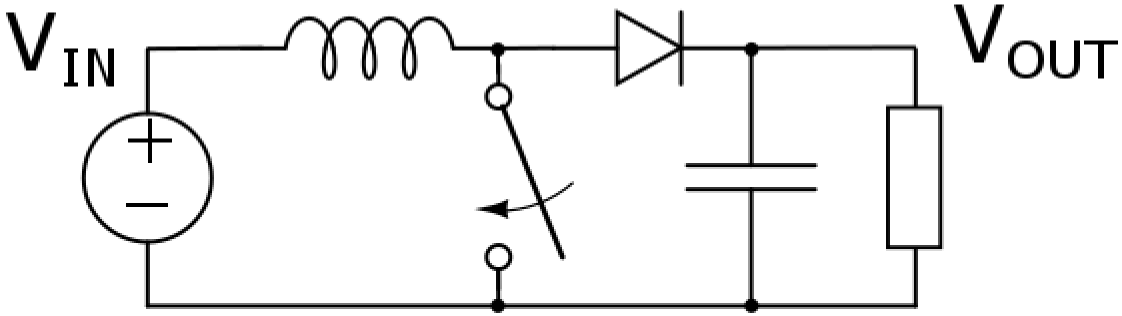
Calculation

- Applying some simplifications the calculation becomes quite easy
  - (the precise calculation is still complicated)
- Assumes the transistor and the diode are ideal switches
- The circuit is analyzed in balanced periodic operating point
- The average voltage of the coil and the average current of the capacitor are zero.
  - Energy in = Energy out
- Kirchhoff-laws are valid for average quantities as well
  - Evidence:
  - $\sum \overline{u_i} = \sum \frac{1}{T} \int u_i(t) dt = \frac{1}{\mathrm{T}} \int [\sum u_i(t)] dt = 0$



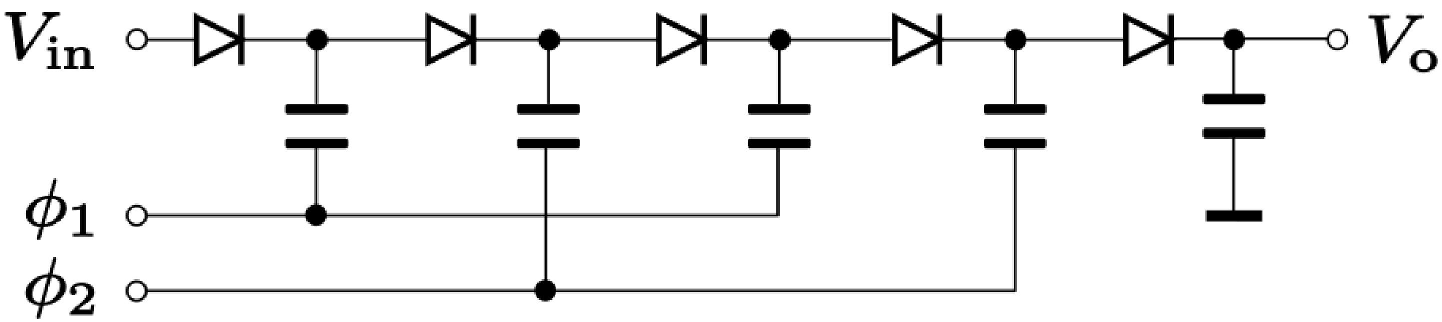
- Applying the average quantities methodology:
- The voltage of the coil
  - If the switch is on: $V_L = V_{IN} - V_{OUT}$
  - If the switch is off: $V_L = -V_{OUT}$
- The average voltage of the coil in a whole period is zero, so:
- $V_L = \delta(V_{IN} - V_{OUT}) + (1 - \delta)(-V_{OUT}) = 0$, where δ is the duty cycle
- Thus, $V_{OUT} = \delta \mathrm{V_{IN}}$
- The output voltage can be controlled by the duty cycle.
  - The ratio between t_{on} and the period T

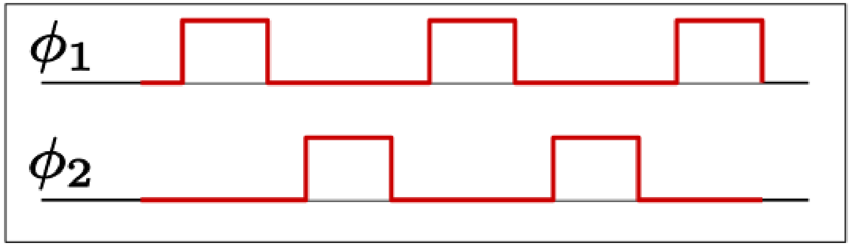
Boost / step-up converter



- It steps up voltage (while stepping down current)
- They are used in hybrid electric vehicles
- Calculation
- $V_L = \delta V_{IN} + (1-\delta)(V_{IN} - V_{OUT}) = 0$
- Thus, $V_{OUT} = \frac{\mathrm{V_{IN}}}{(1-\delta)}$
- The practical limit is ~ 5x the input voltage

Charge pumping



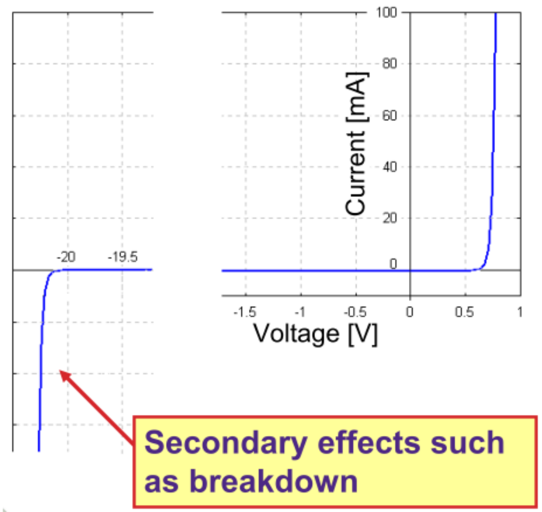


- Only capacitors are used as energy storing elements
- It requires a high frequency two-phase control signal
- Easy to implement using CMOS technology

Usage of charge pumping circuits

- Applying transmission gates instead of diodes this circuit becomes CMOS compatible
- They can provide the erasure and programming voltage (10-20V) in EEPROM and FLASH memory
  - Level shifter circuits, e.g. in MAX232 ± 7.5V from 5V power supply
  - Gate drivers, to provide the higher gate-source voltage
    - (reducing the channel resistance of the transistor)
  - LCD drivers
  - etc.
- It requires fewer components, and is a simpler circuit than the coil-based ones

Diodes in reverse direction

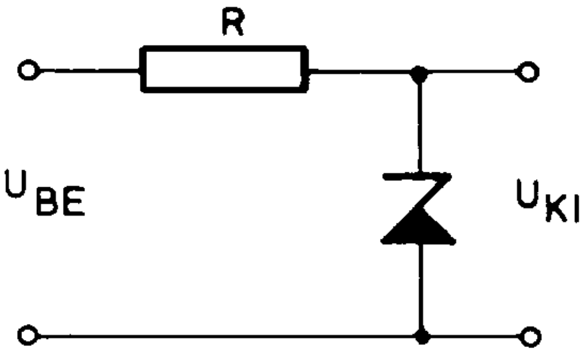


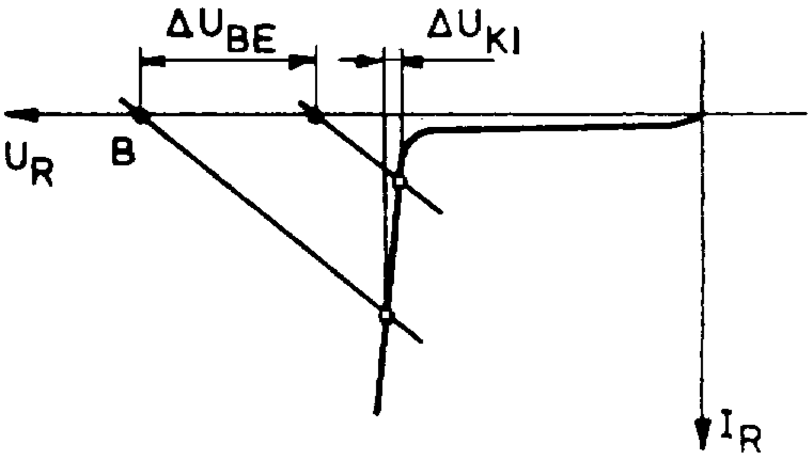
- In the reverse direction: the reverse current of the diode starts to increase steeply with the voltage at the breakdown voltage V_{BR}
- If the diode's current is limited by external means, the breakdown state does not harm the structure.
- As a very small change in the reverse voltage results in a big change in the reverse current at the breakdown state, it can be used to stabilize voltage.
- Zener diodes: special diodes created to serve as a voltage stabilizer in the breakdown state.

Voltage regulation

- The aforementioned DC-DC conversion techniques cannot provide absolutely smooth output voltage and current
  - The output voltage ripple can be reduced using smoothing capacitors, but it is impossible to eliminate totally
  - Sensitive (analog) circuits required stabilized/regulated supply and bias voltages
- A voltage regulator is designed to automatically maintain a constant voltage level
  - Feedback voltage regulators operate by comparing the actual output voltage to some fixed reference voltage
- The output voltage is always lower than input voltage
- Dropout voltage: smallest possible difference between the input voltage and output voltage to remain inside the regulator's intended operating range.

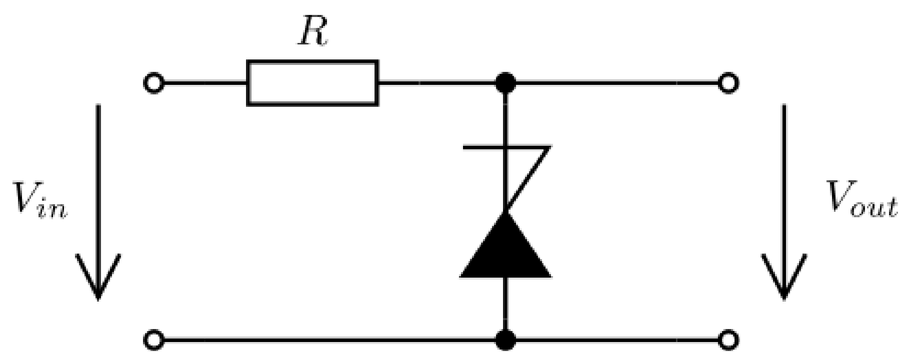
Zener diode





- If the input voltage is larger than the breakdown voltage the diode is in the breakdown state.
- The I-V curve is very steep at the breakdown voltage
  - Large changes in current causes small changes in voltage

Zener diode - example



- Let's calculate the voltage drop and the current of a Zener-diode if V_{in}=12V, R=100Ω, and the breakdown voltage is 5.6V!

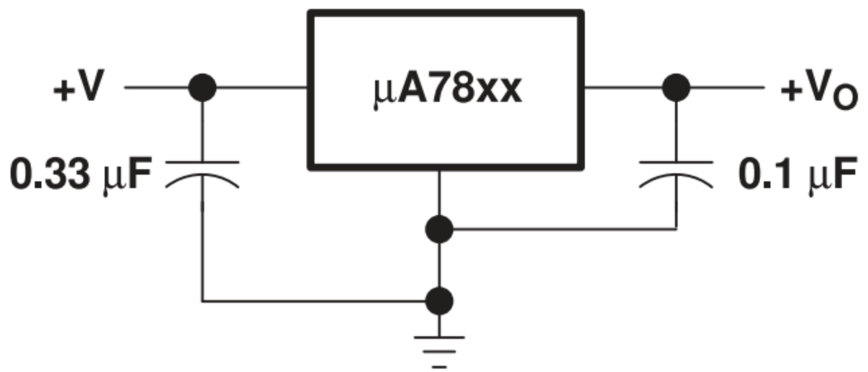
$$I \cong \frac{V_{in} - V_Z}{R} = \frac{12 - 5.6}{0.1} = 64mA$$

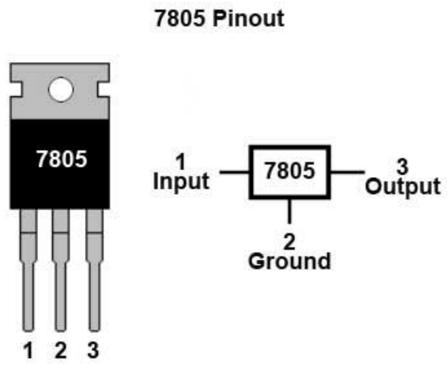
- How much does the output voltage change if the input changes by 1 V? (The differential resistance is: 2 Ω.)

$$v_{out} = v_{in} \cdot \frac{r_d}{R_t + r_d} = \frac{2}{102} = 20mV$$

- Thus the change at the input is reduced to 1/50 of its value!

Voltage regulation – in practice





- Commercial off-the-shelf (COTS) circuits
- E.g. 78XX series

Power supply

- Usually they contain a switching power supply
- They have wide input voltage
  - Generally 80-250V
- The conversion is done in the following steps:
  - Rectification – smoothing – DC/DC conversion – regulation (if necessary)
- The smoothing process causes a big problem:
  - The input current of the power supply exists only when the input voltage exceeds voltage of the smoothing capacitor
  - The shape of the current signal is not sinusoidal
  - Problems:
    - It overloads the electrical grid (by 25-30%)
    - It generates noise

Power factor correction (PFC)

- After rectification (Grätz-bridge), the smoothing capacitor is replaced by a boost converter which provides real direct current/voltage
- This voltage is higher than the peak voltage of the input voltage (380-400V)
- The current is controlled in a special way: the current follows the variation of the input voltage
  - Changing the duty cycle…
- E.g.: http://www.ti.com/product/ucc29950/datasheet
- Price: 75cents…