ELECTRICAL ISSUES

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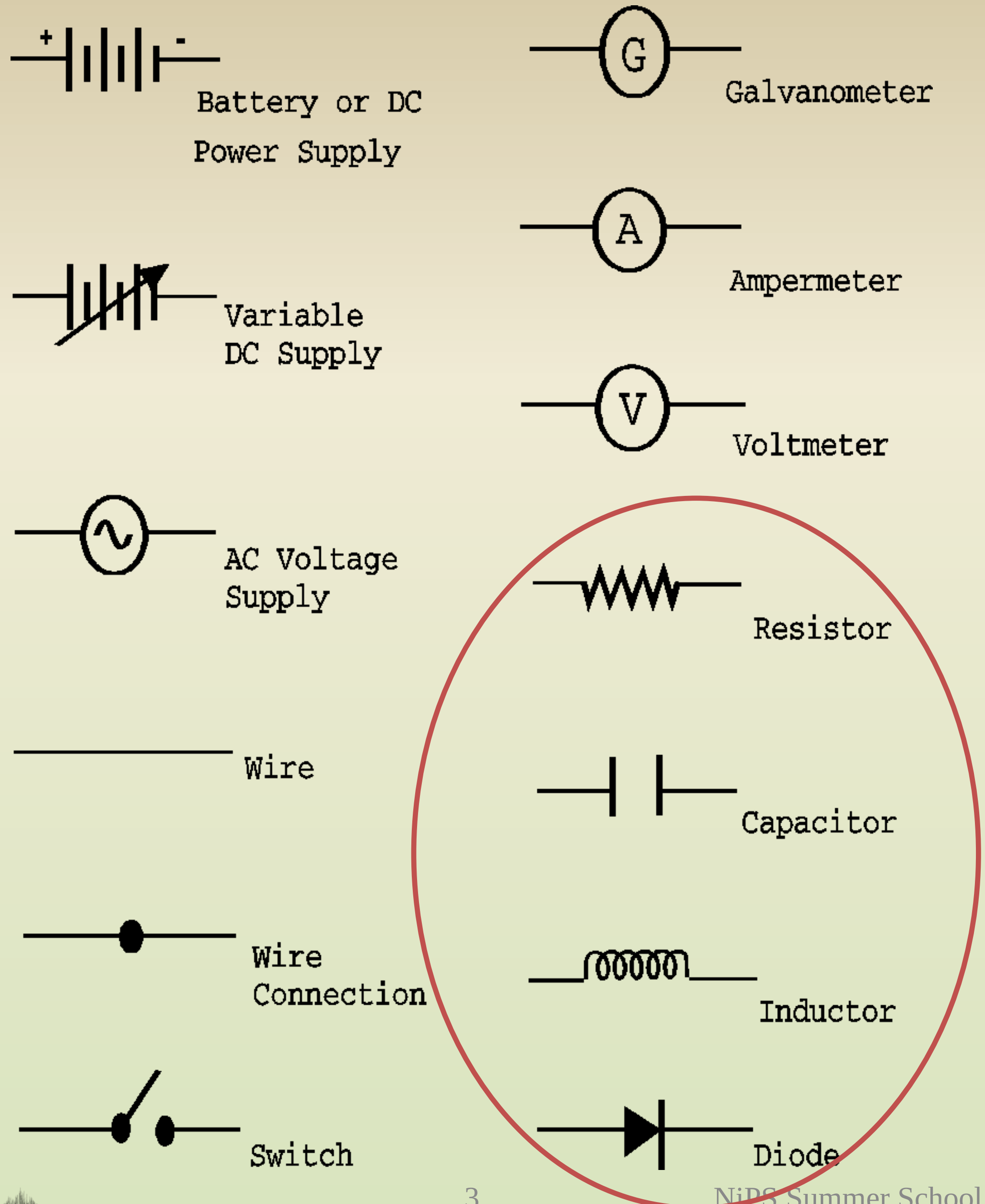
NiPS Laboratory
Noise in Physical Systems

Outline

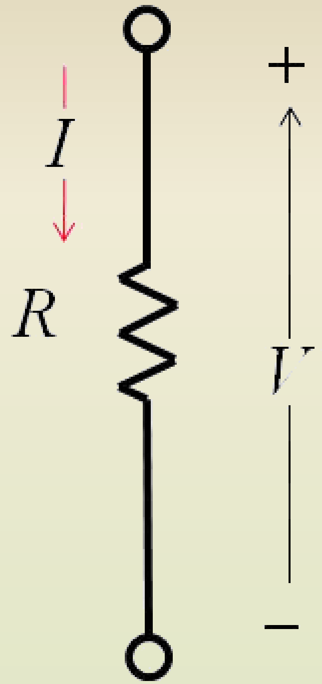
- *Introduction*
- *Electrical impedance matching*
- *Electrical energy conversion*
- *Energy storage*
- *Power management*

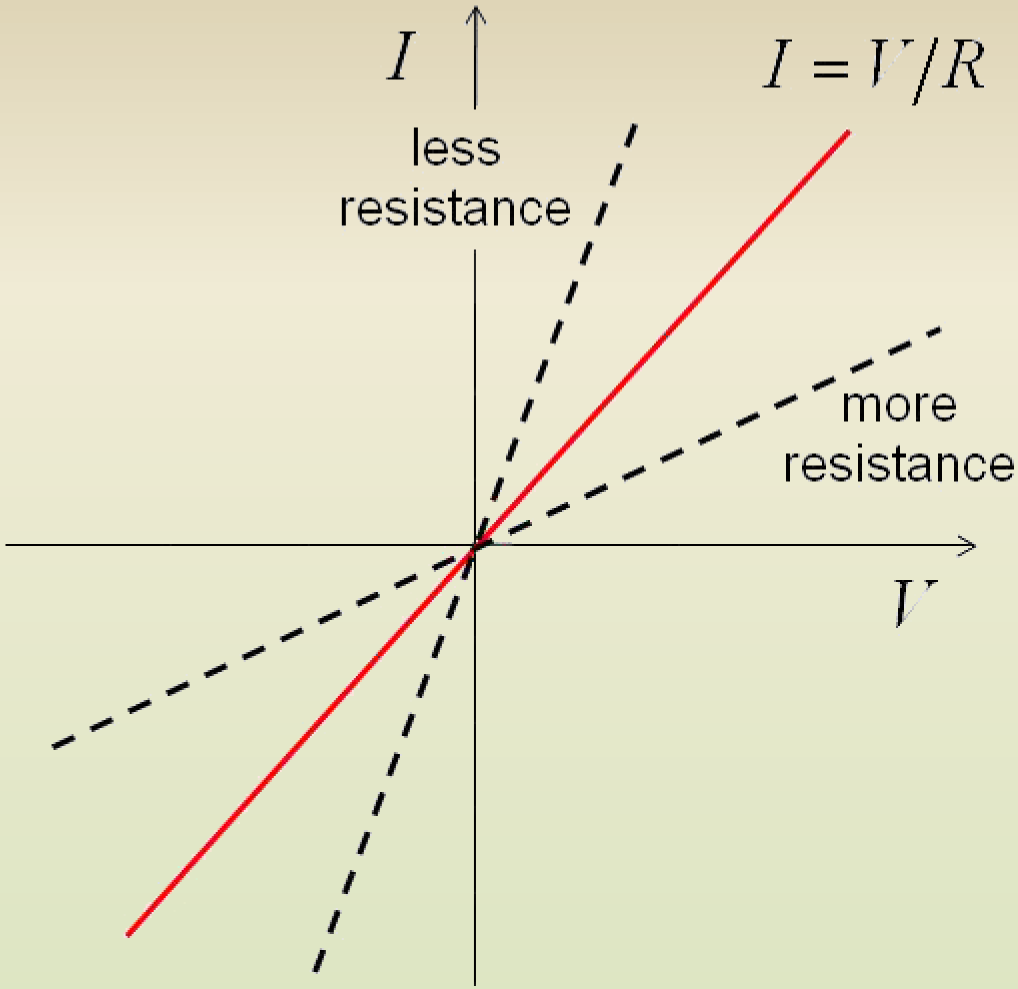
Introduction



Introduction

Resistor



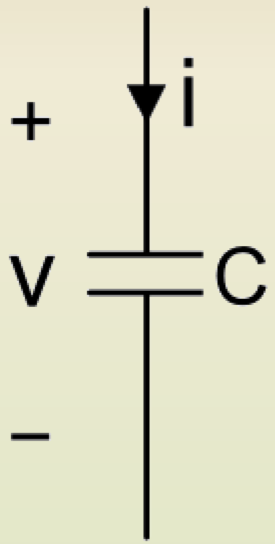


I=V/R   *Ohm's law*

George Ohm, 1827

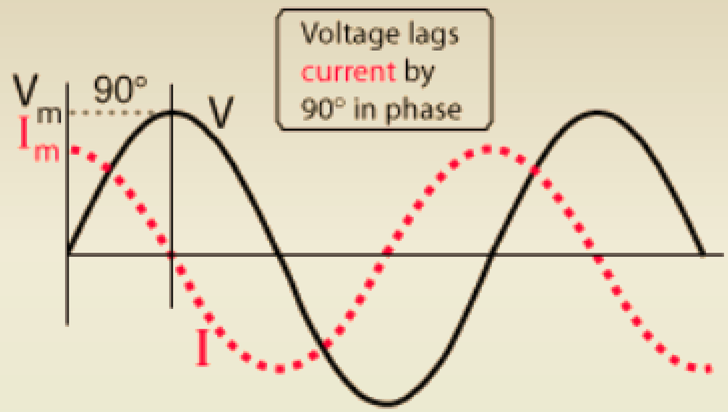
Introduction

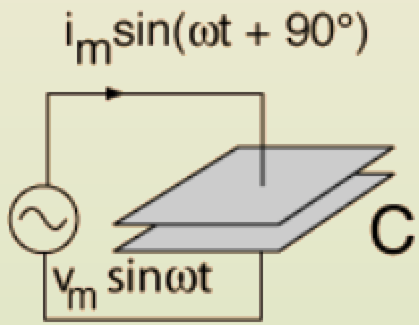
Capacitor



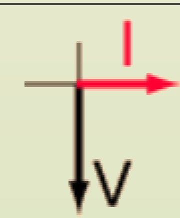
$$I = \frac{V}{X_C}$$

$$X_C = \frac{1}{\omega C}$$





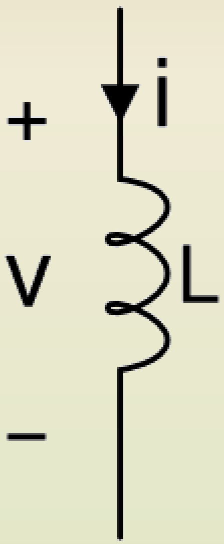
$$I = \frac{I_m}{\sqrt{2}},\ V = \frac{V_m}{\sqrt{2}}$$

Contribution to complex impedance	Phasor diagram
$\frac{-j}{\omega C}$	

At DC (0 Hz) a capacitor acts like an open-circuit!!!

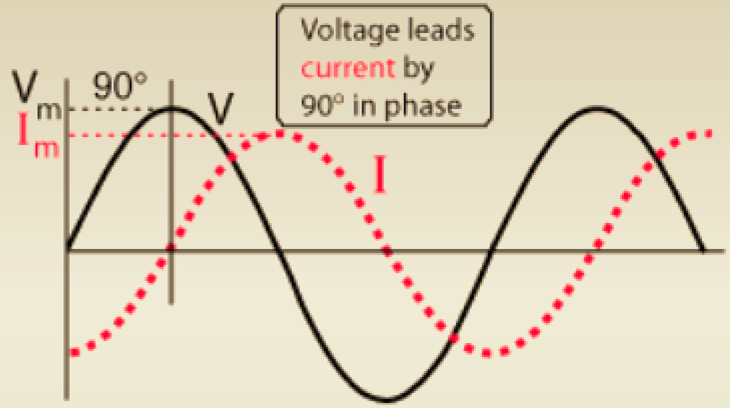
Introduction

Inductor

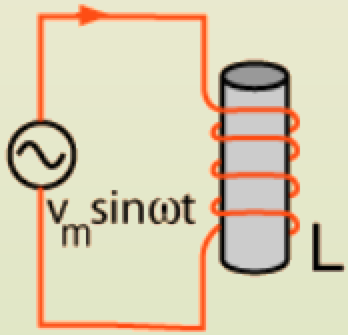


$I = \frac{V}{X_L}$

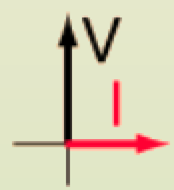
$X_L = \omega L$



$i_m \sin(\omega t - 90°)$



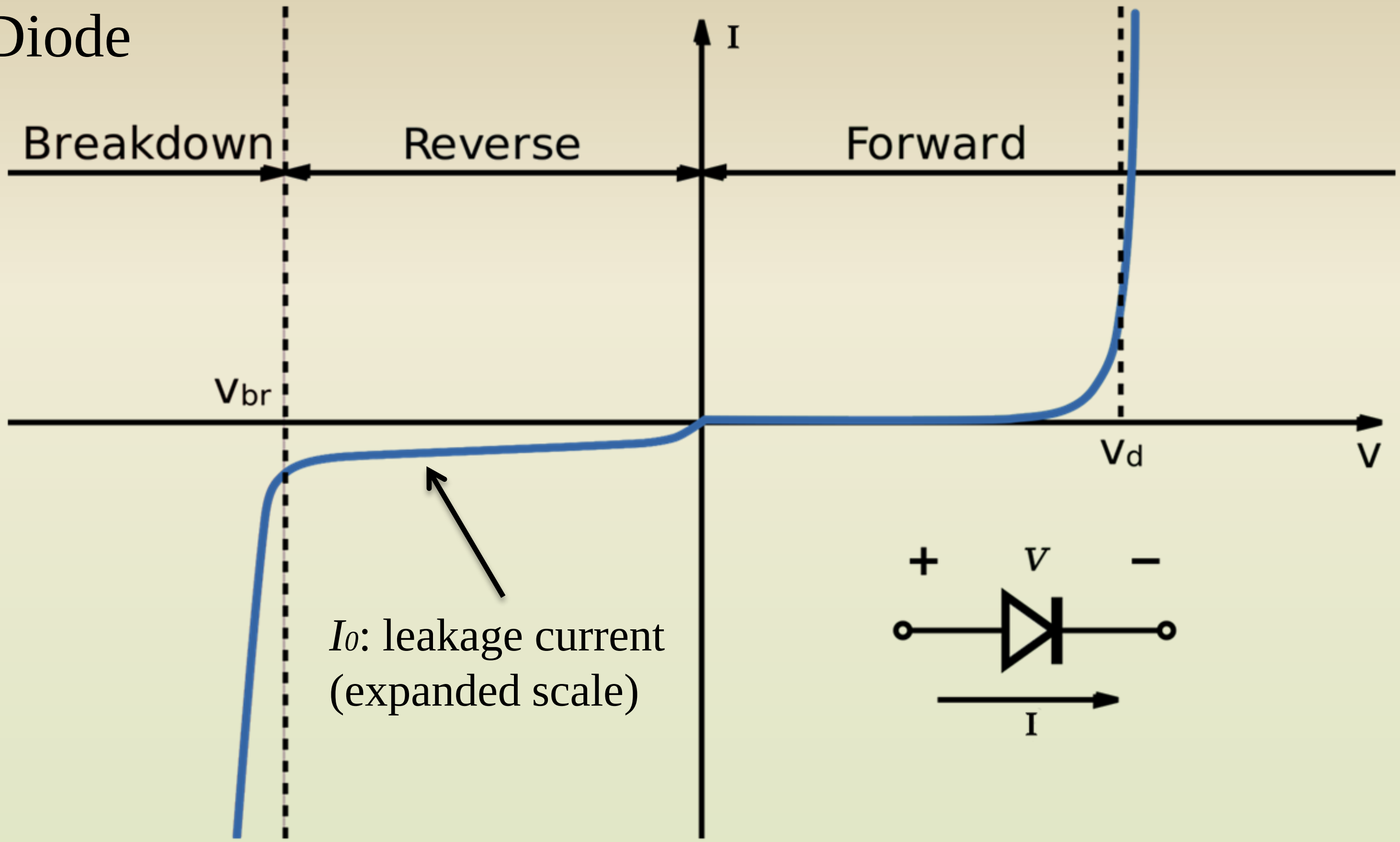
$I = \frac{I_m}{\sqrt{2}},\ V = \frac{V_m}{\sqrt{2}}$

Contribution to complex impedance	Phasor diagram
$j\omega L$	

At DC (0 Hz) an inductor acts like a short-circuit!!!

Introduction

Diode



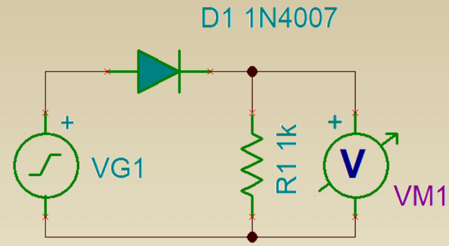
Shockley diode equation

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

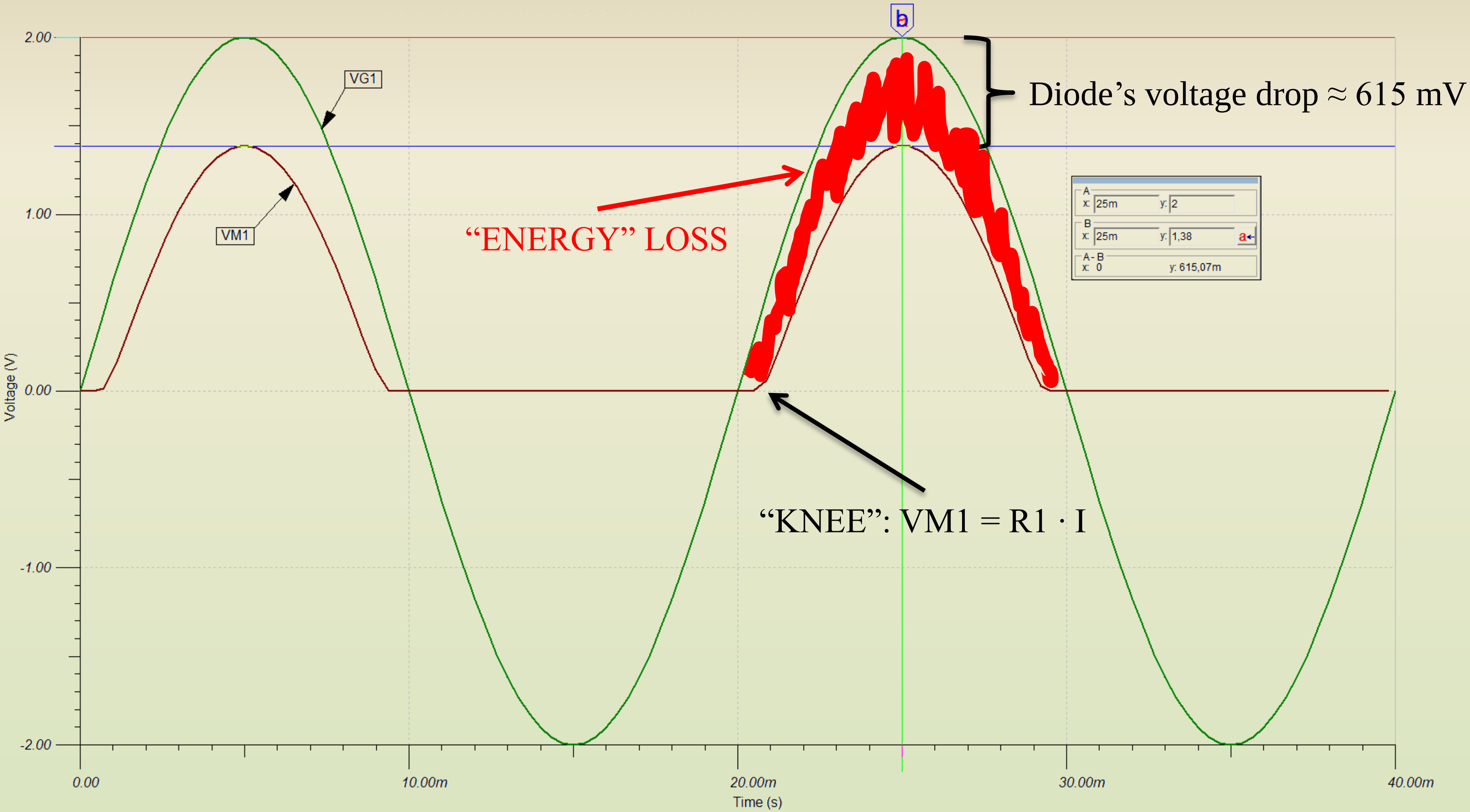
I_0 = "dark saturation current", reverse bias saturation current
V = applied voltage across the terminals of the diode
q = absolute value of electron charge 1.6021766208(98)×10^{-19} C
k = Boltzmann’s constant, 1.38064852(79)×10^{-23} J/K
T = absolute temperature (K)
n = ideality factor (quality factor)

Introduction

Example



VG1: sinusoidal voltage generator, 50 Hz, 4Vpp
D1: silicon diode
R1: 1 kOhm resistor
VM1: voltmeter



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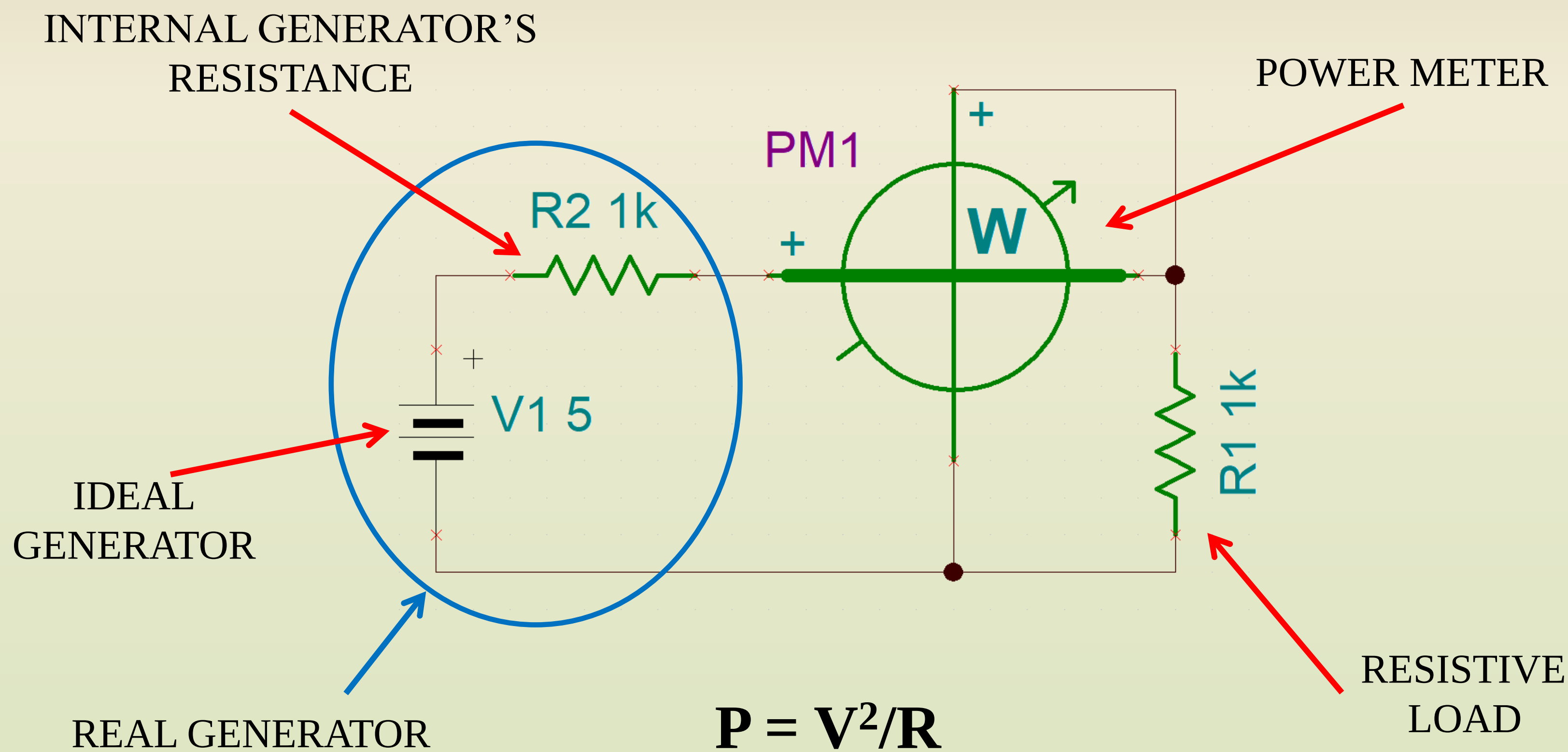
Electrical impedance matching

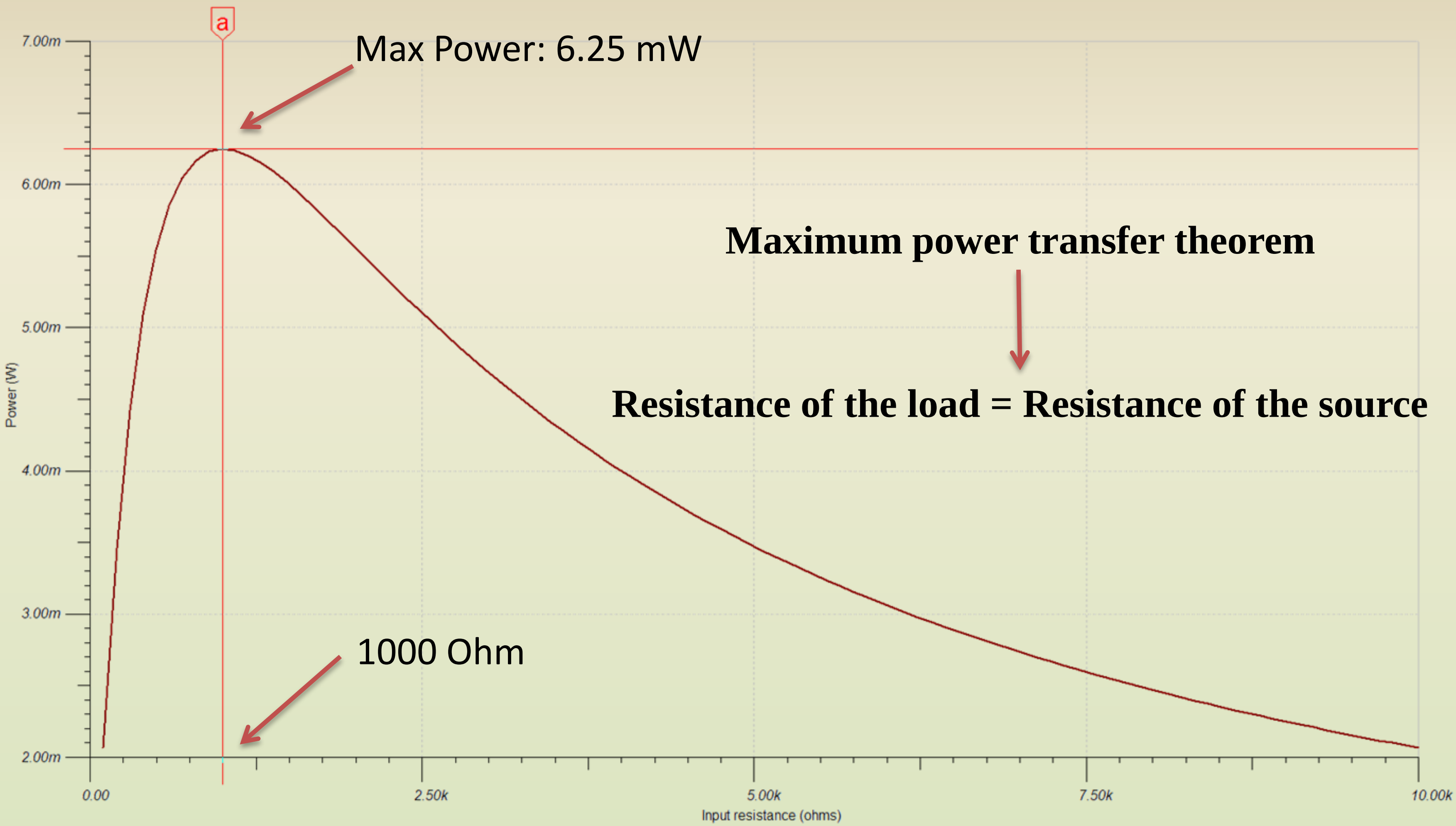
What about the power dissipated by R1?



$$P = V^2/R$$

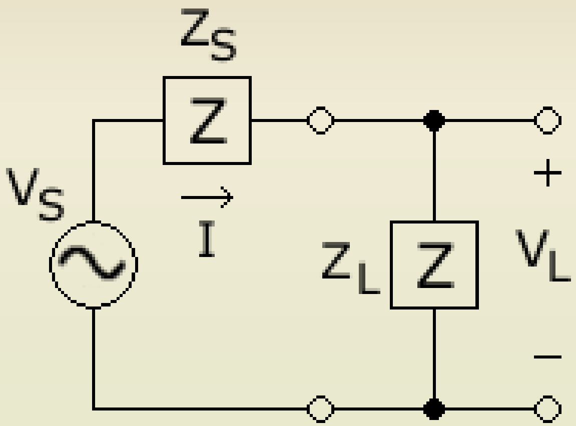
Electrical impedance matching

Power as fuction of R1, from 100 Ohm to 10000 Ohm



Electrical impedance matching

What about the power dissipated in alternating current regime?



$$|I| = \frac{|V_S|}{|Z_S + Z_L|}.$$

$$P_L = I_{rms}^2 R_L = \frac{1}{2}|I|^2 R_L = \frac{1}{2}\left(\frac{|V_S|}{|Z_S + Z_L|}\right)^2 R_L$$

$$= \frac{1}{2}\frac{|V_S|^2 R_L}{(R_S + R_L)^2 + (X_S + X_L)^2},$$

R_S, R_L: resistance of the generator and of the load (real part of Z_S and Z_L)

X_S, X_L: reactance of the generator and of the load (imaginary part of Z_S and Z_L)

Electrical impedance matching

MAX of

$$P_L = I_{rms}^2 R_L = \frac{1}{2}|I|^2 R_L = \frac{1}{2}\left(\frac{|V_S|}{|Z_S + Z_L|}\right)^2 R_L$$

$$= \frac{1}{2}\frac{|V_S|^2 R_L}{(R_S + R_L)^2 + (X_S + X_L)^2},$$

min of $(R_S + R_L)^2 + (X_S + X_L)^2$ $R_S, R_L > 0$

$X_L = -X_S.$ $\Longrightarrow$ $P_L = \frac{1}{2}\frac{|V_S|^2 R_L}{(R_S + R_L)^2}$

Maximum Power Transfer Condition

$R_L = R_S$ $\Longrightarrow$ $Z_L = Z_S^*.$ $\Longleftarrow$ $X_L = -X_S$

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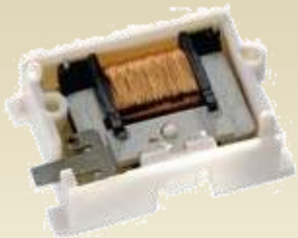
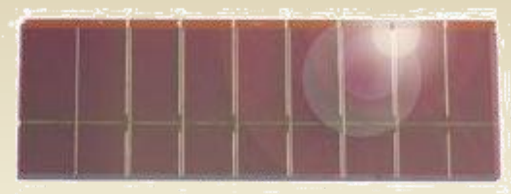
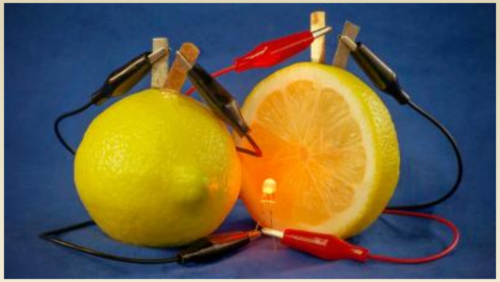
Electrical energy conversion

Electrical energy sources

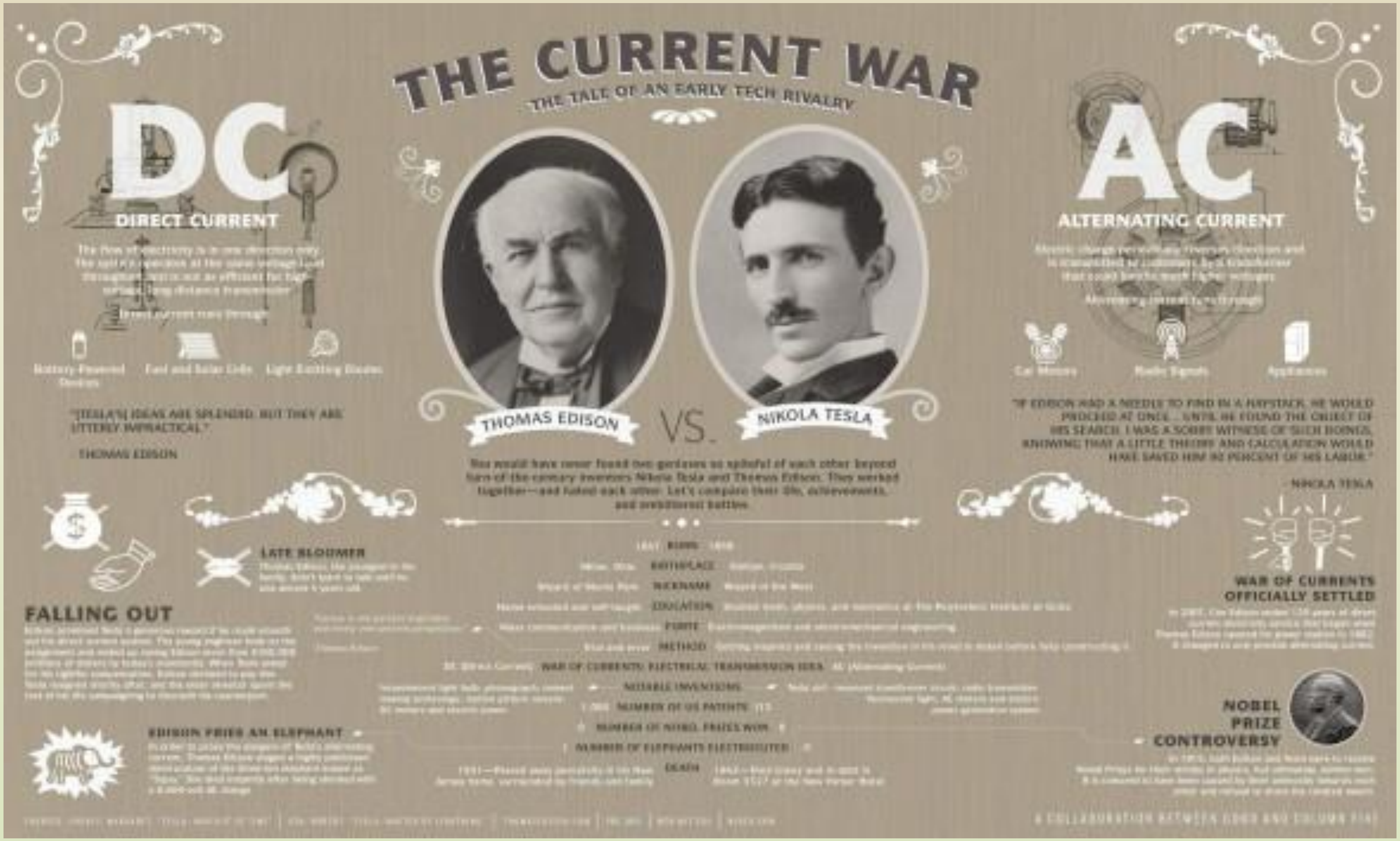



Electrical energy conversion

Deep inside, are these devices AC powered or DC powered?

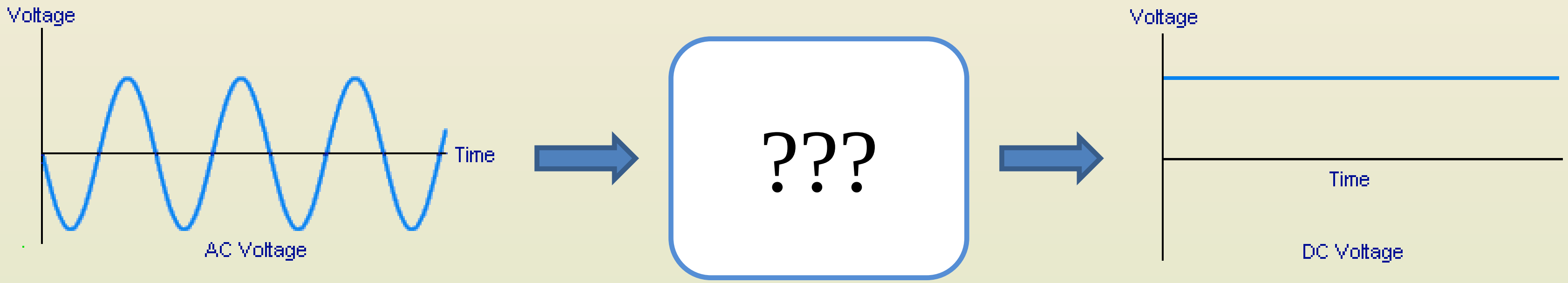
Electrical energy conversion

AC or DC?
A war from the late 19° century



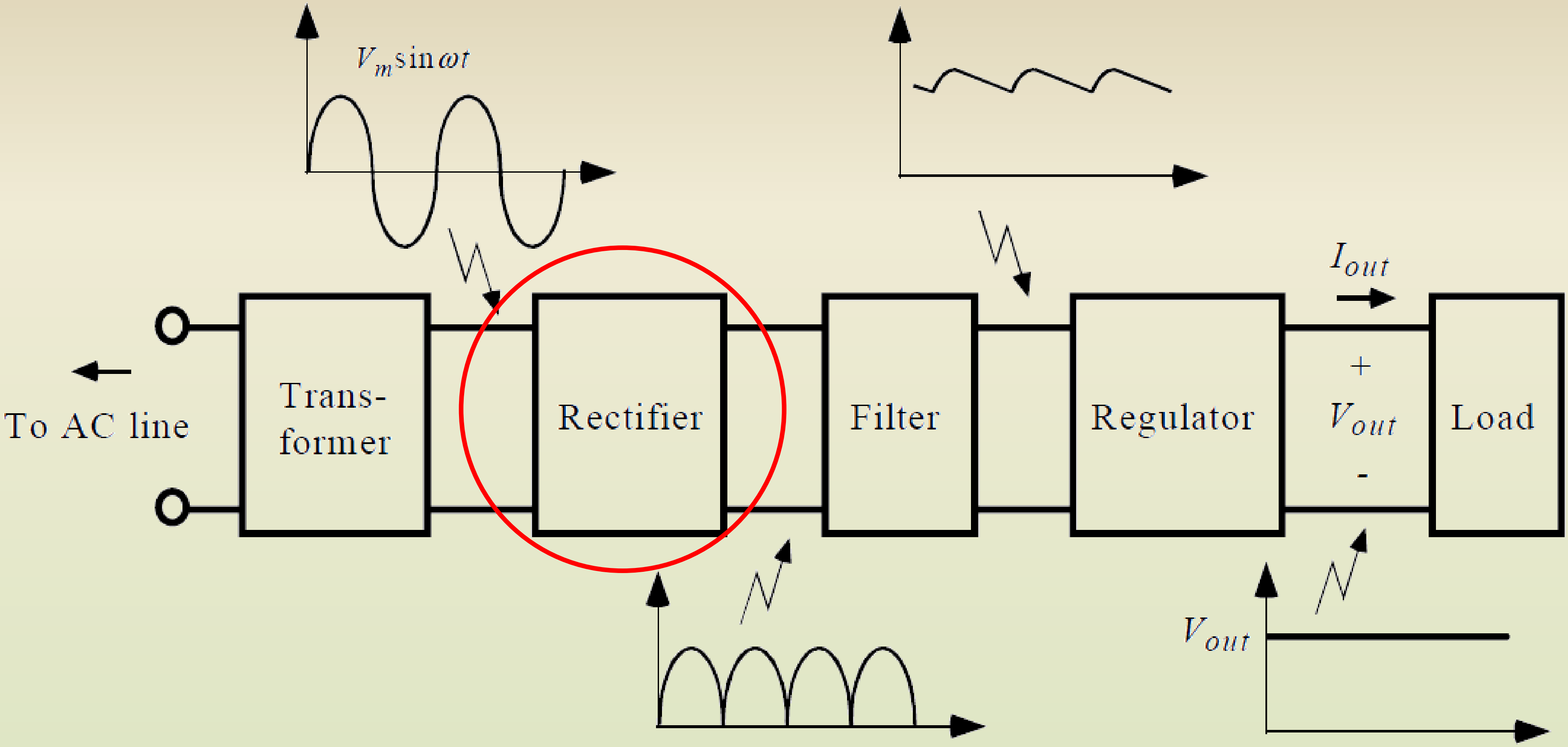
Electrical energy conversion

How DC powered devices are AC powered?



Electrical energy conversion

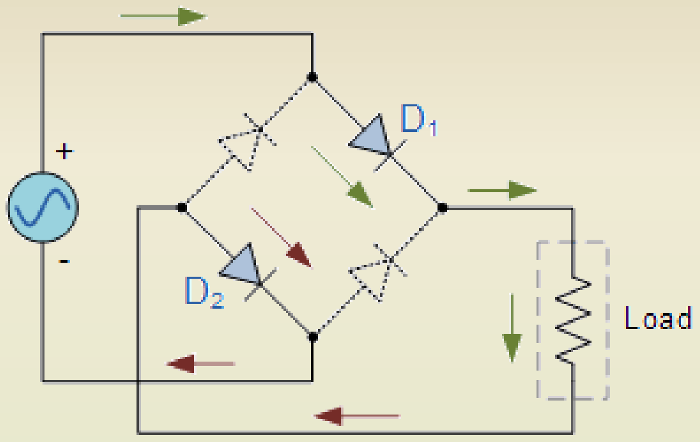
How DC powered devices are AC powered?

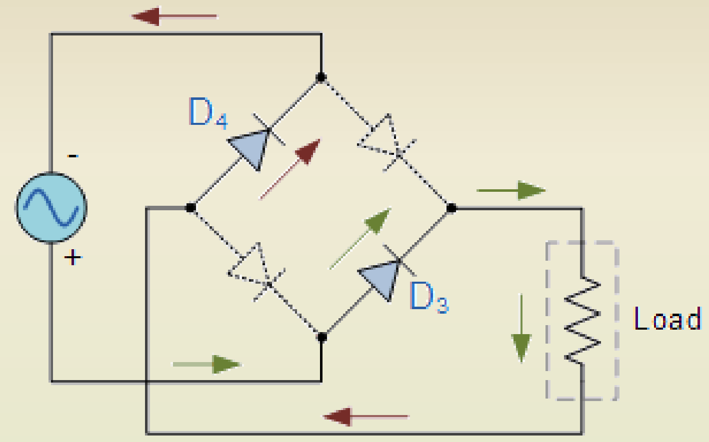


Components of a typical linear power supply

Electrical energy conversion

AC to DC conversion



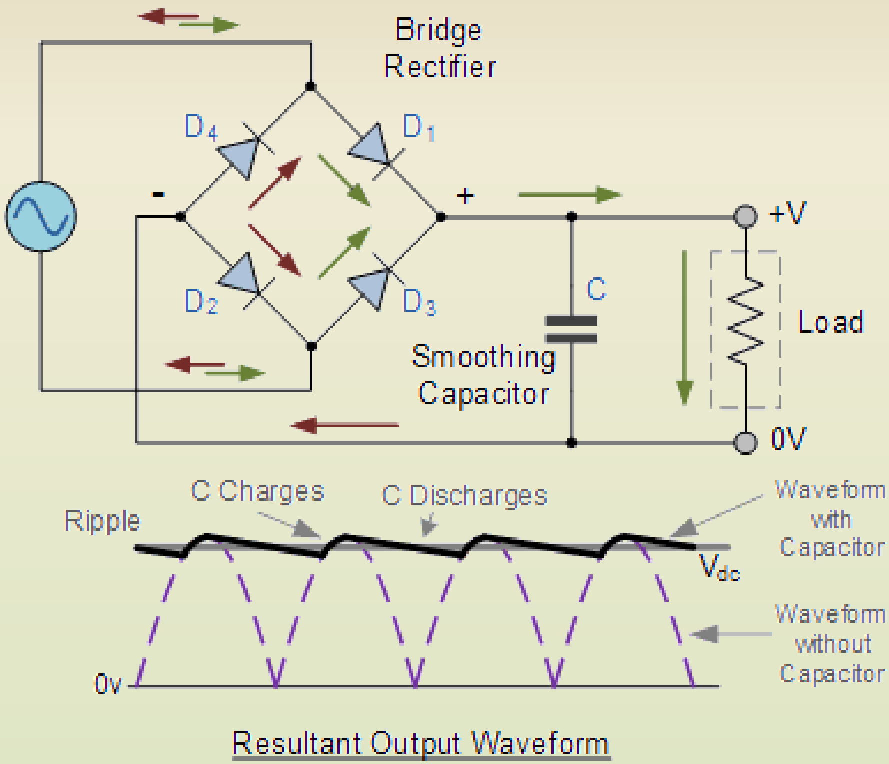


The Positive Half-cycle

The Negative Half-cycle

Electrical energy conversion

AC to DC conversion



Bridge Rectifier Ripple Voltage

$$Ripple = \frac{I_{load}}{f \cdot C} \quad V$$

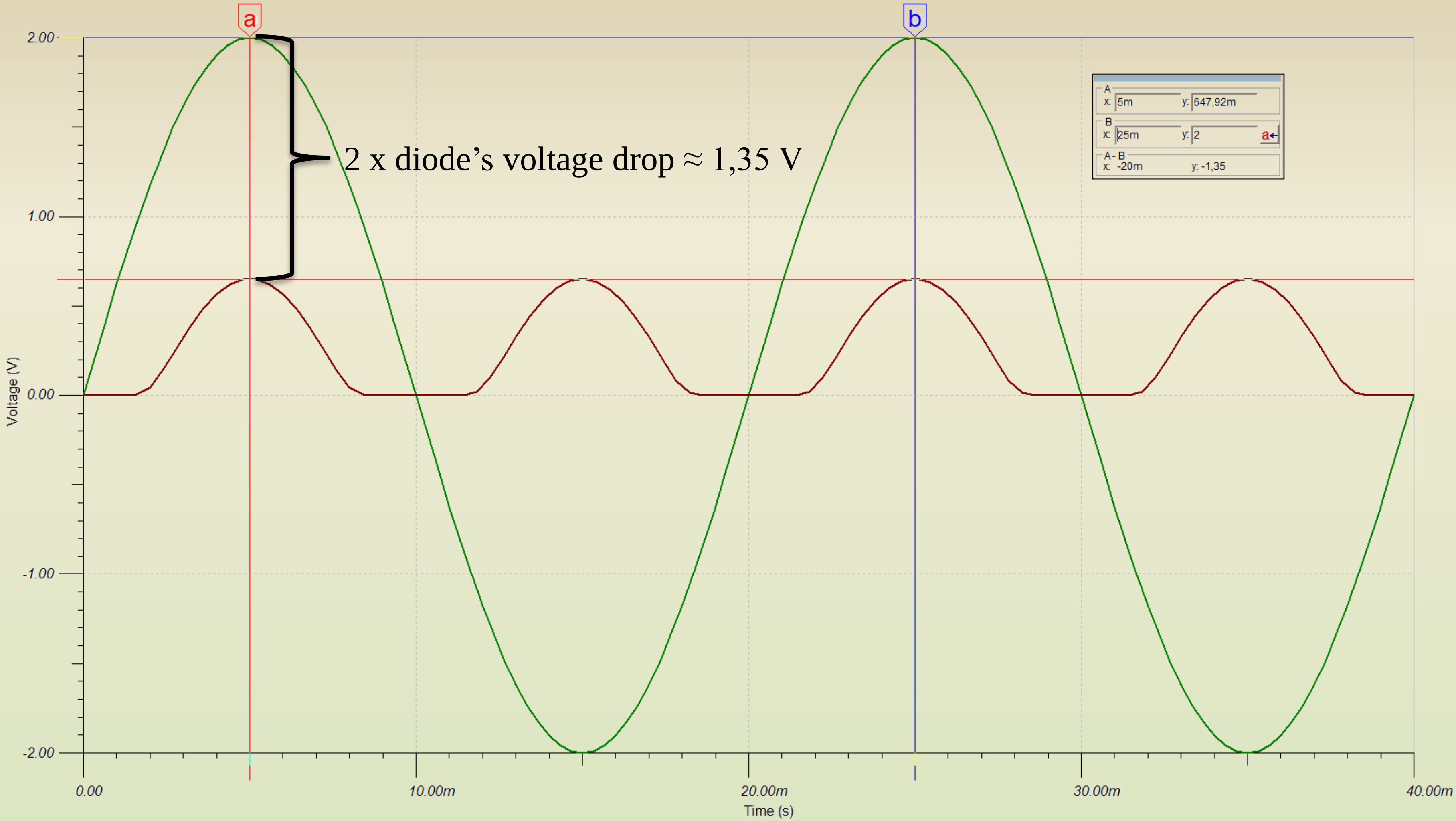
I_{load} load current

f frequency

C capacitance in Farads

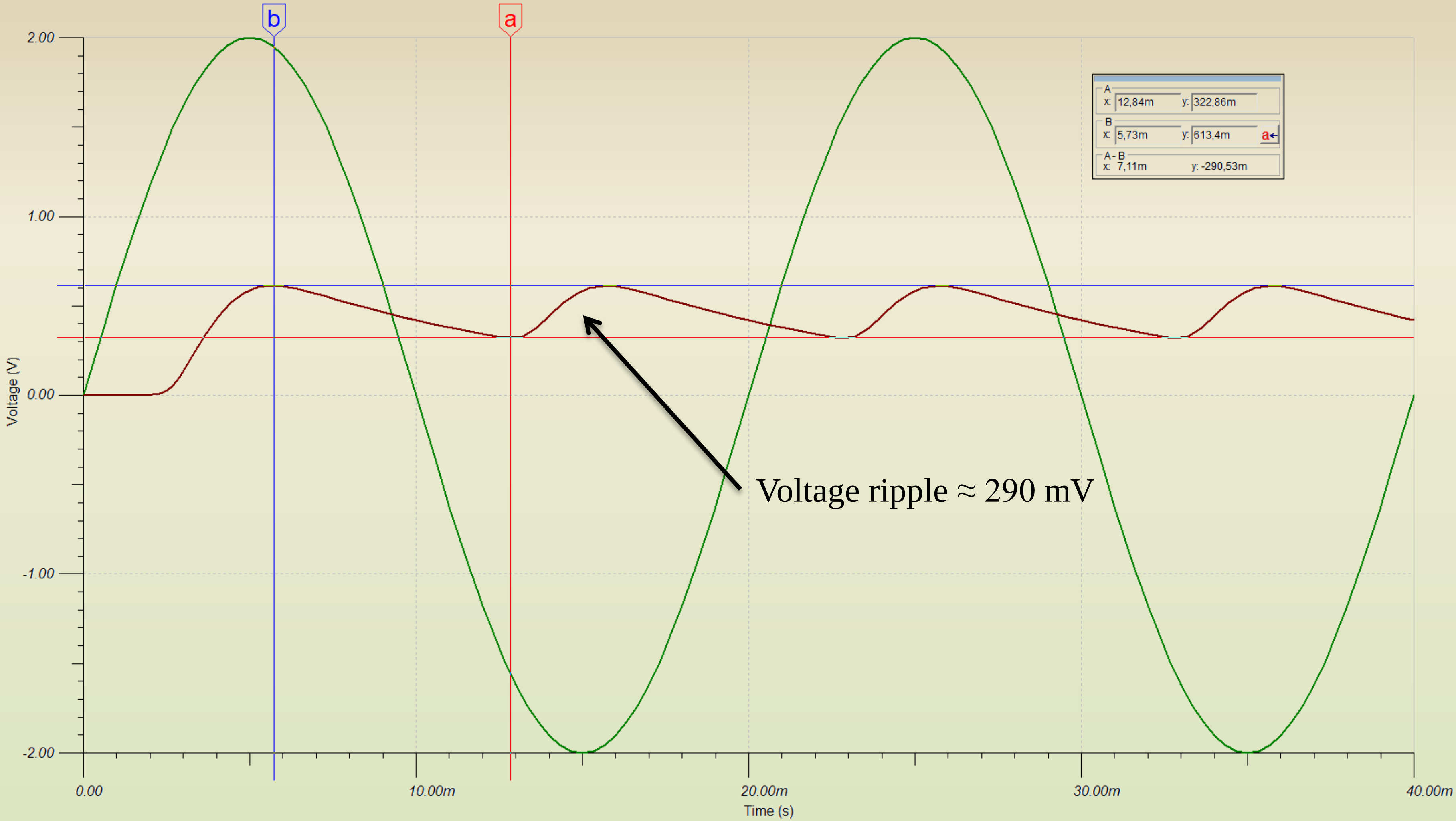
Electrical energy conversion

4 diodes bridge rectifier



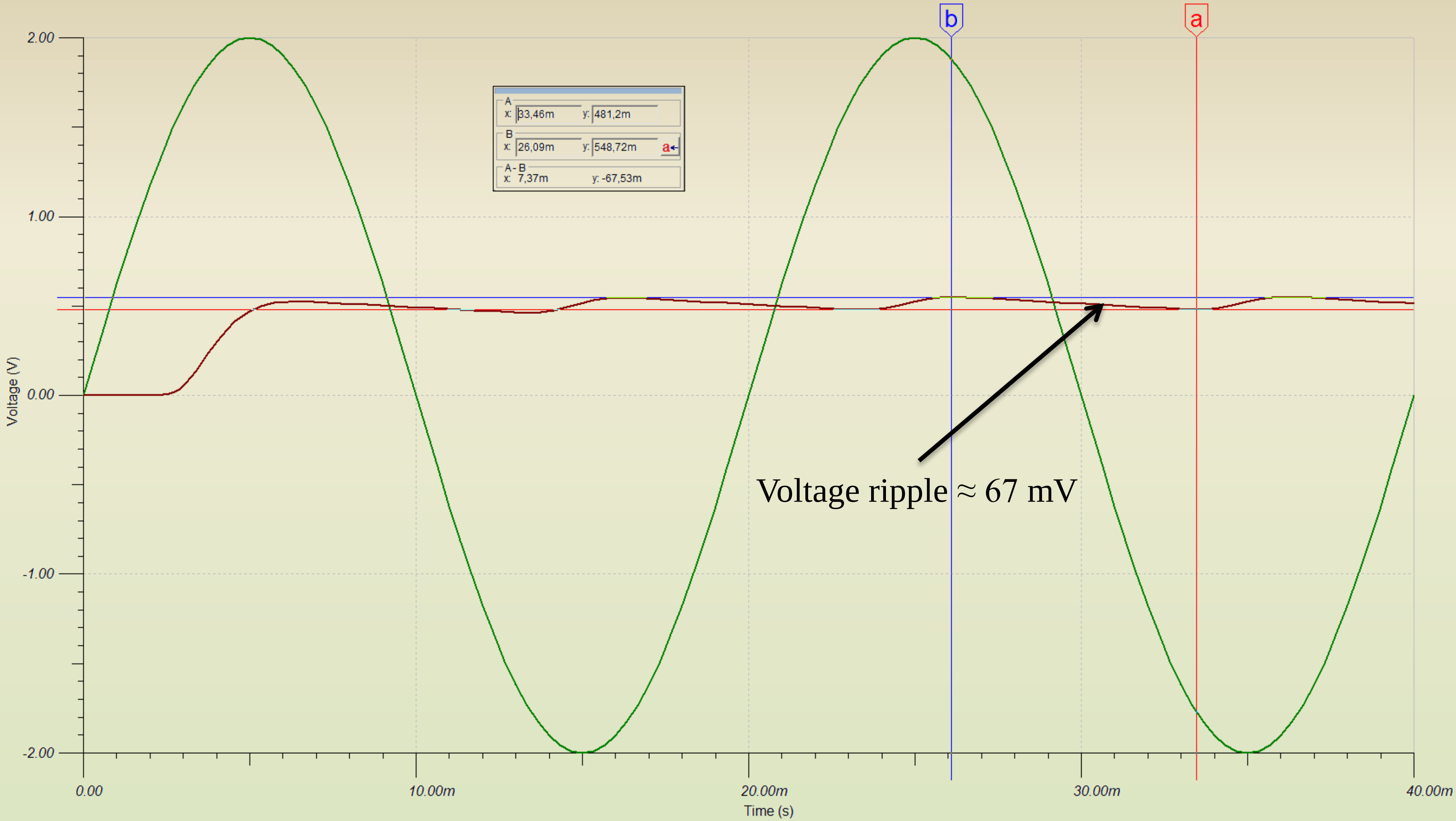
Electrical energy conversion

4 diodes bridge rectifier + 100μF capacitor



Electrical energy conversion

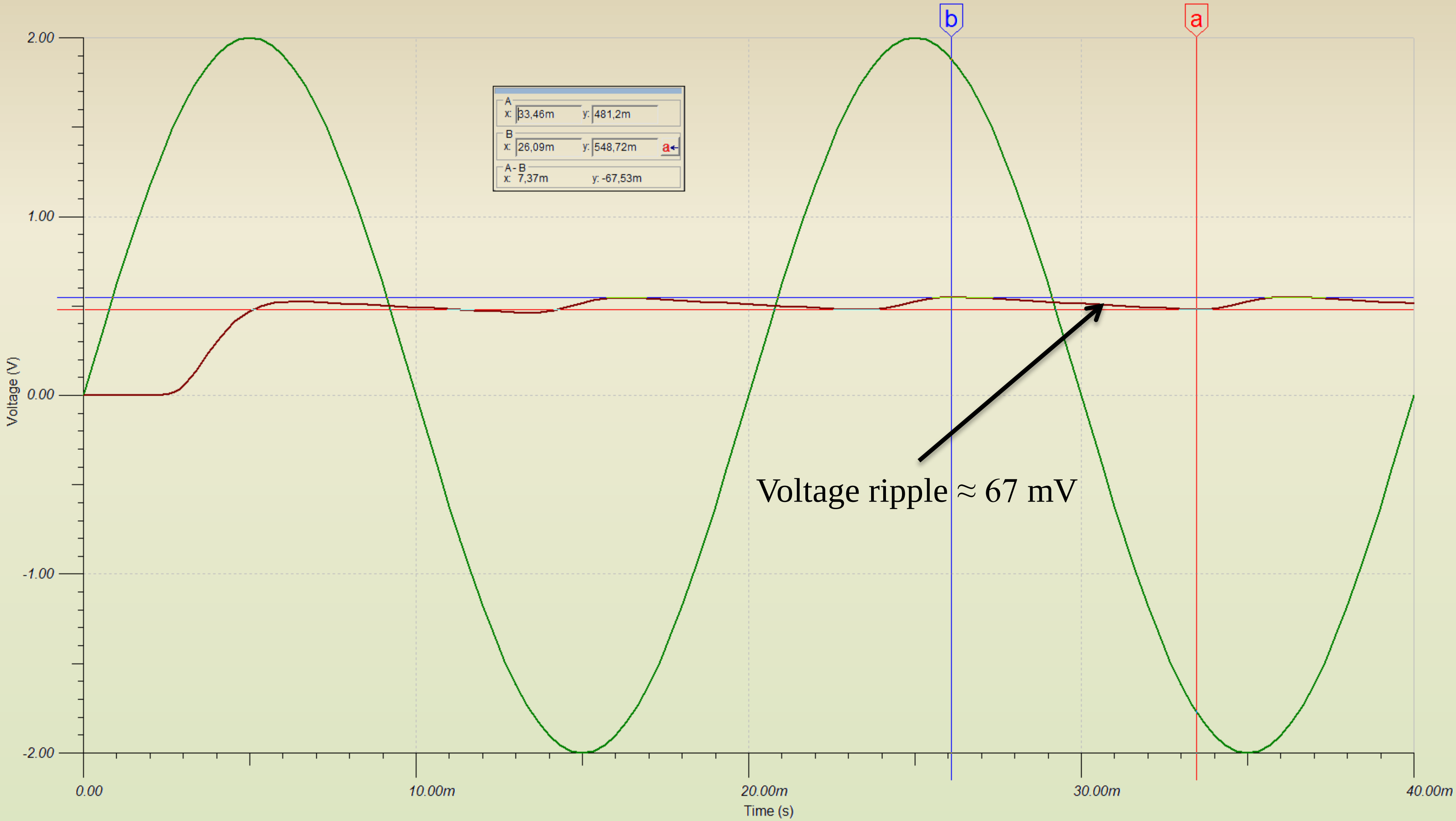
4 diodes bridge rectifier + 500µF capacitor



Voltage ripple ≈ 67 mV

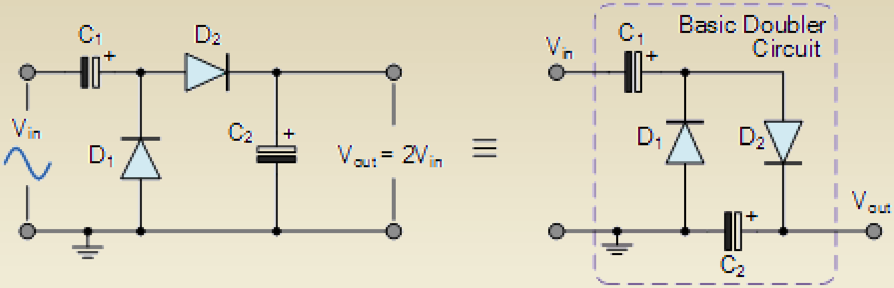
Electrical energy conversion

4 diodes bridge rectifier + 500µF capacitor



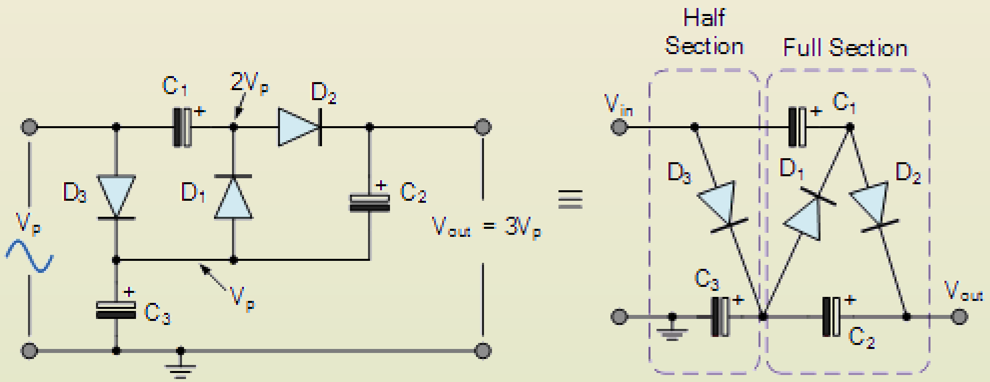
Electrical energy conversion

Voltage rectifier and multiplier



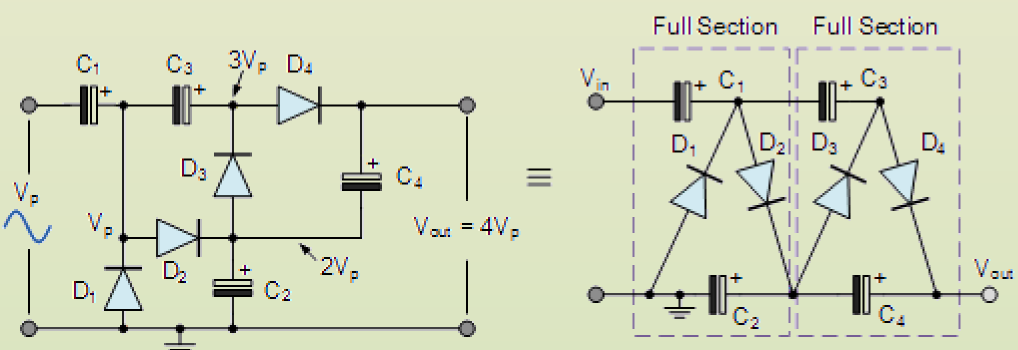
Voltage Doubler Circuit

$$V_{out} = 2 \cdot V_{in}$$



Voltage Tripler Circuit

$$V_{out} = 3 \cdot V_{in}$$



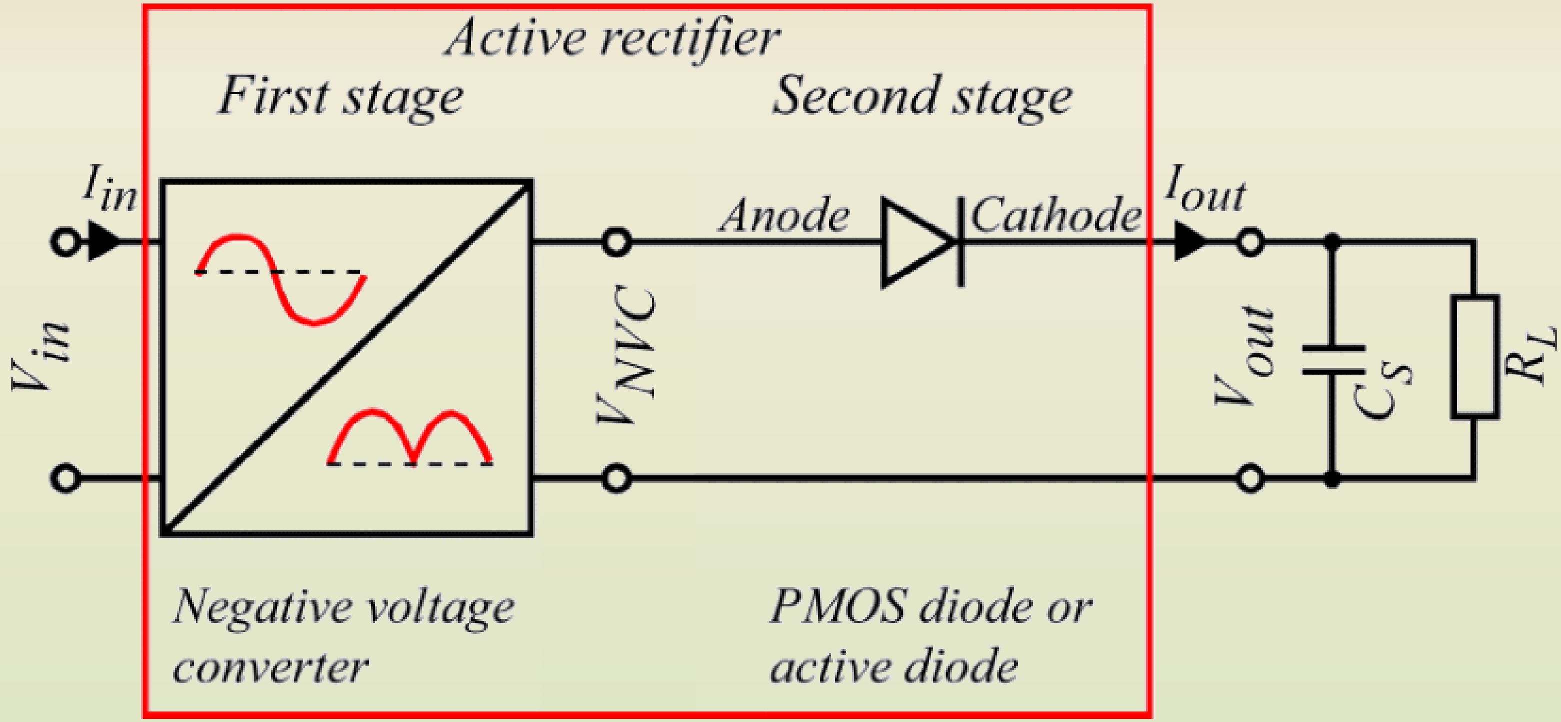
Voltage Quadrupler Circuit

$$V_{out} = 4 \cdot V_{in}$$

Electrical energy conversion

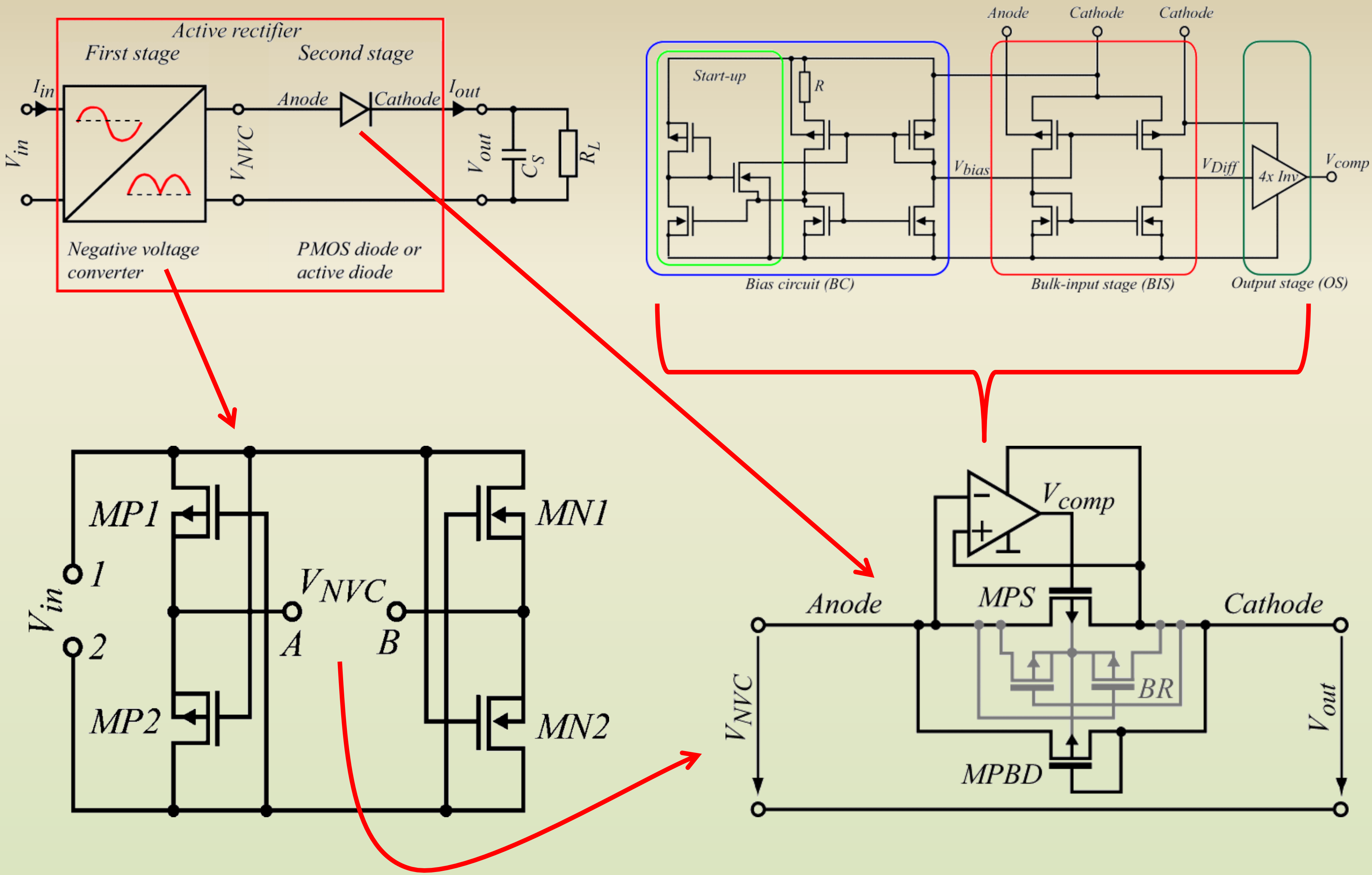
How to reduce the voltage drop of the diodes?

Active (controlled) diodes!

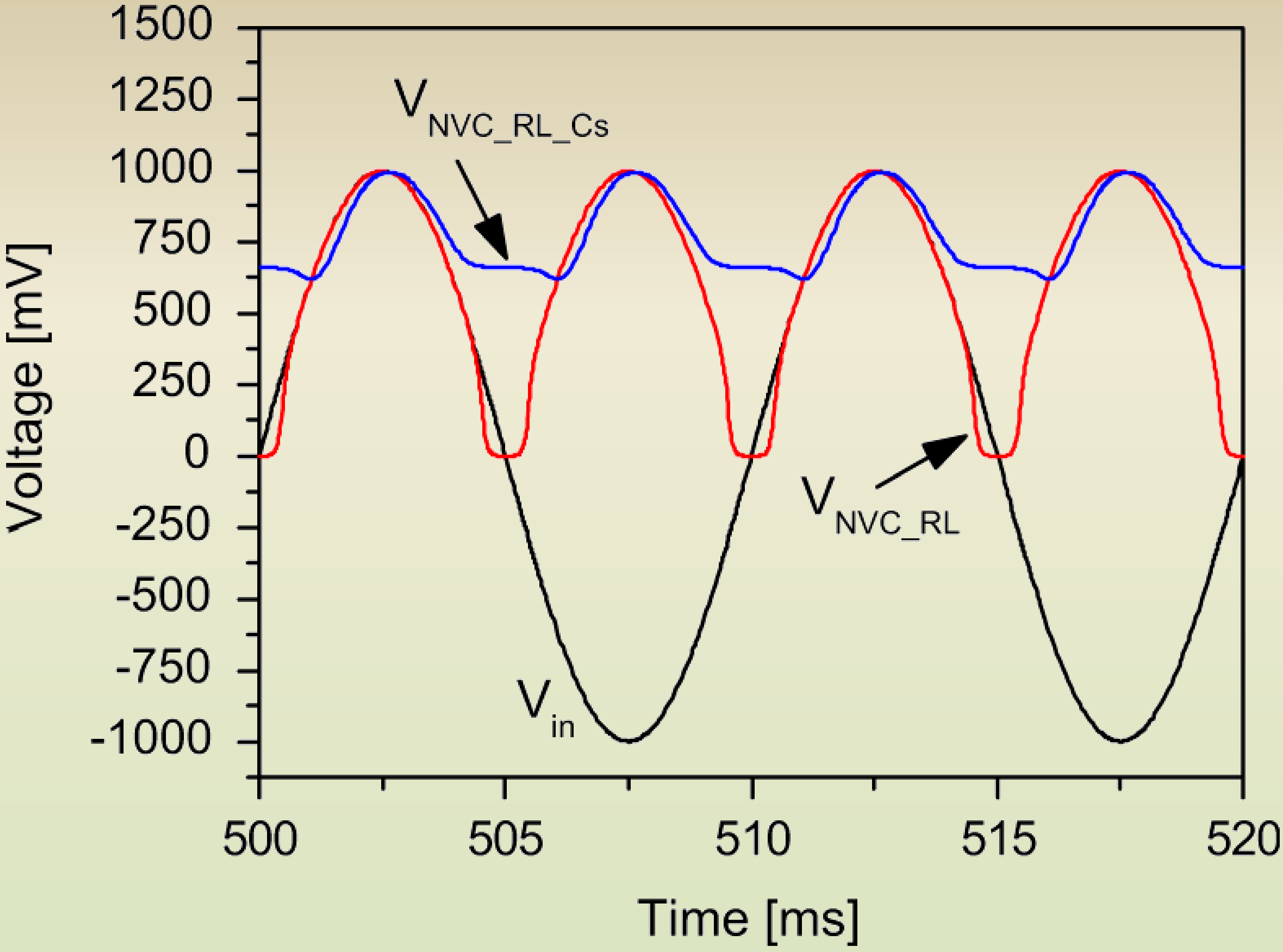


C. Peters, J. Handwerker, D. Maurath and Y. Manoli, "**A Sub-500 mV Highly Efficient Active Rectifier for Energy Harvesting Applications**," in *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, no. 7, pp. 1542-1550, July 2011. doi: 10.1109/TCSI.2011.2157739

Electrical energy conversion



Electrical energy conversion



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- *Power management*

Energy storage

Which energy storage technology can meet my needs?

Electrical energy storage is key to balancing the supply and demand of energy, optimising our use of intermittent energy sources such as wind or solar, and also enabling the electrification of transport.* Here's our guide to energy storage technologies.

Where is the storage technology needed?

Grid What will the technology be used for?

Transport What form of transport?

Stationary electric vehicles may provide storage for the grid

Seasonal storage Requirement: Large storage capacity, slow discharge
1 5

Daily peak shifting Requirement: Hours of available supply
1 2 3 5 6 7 8

Grid support / balancing intermittency Requirement: Fast response, seconds to hours of available supply
1 3 4 6 7 8

Road Requirement: High power and small unit size
5 6

Shipping / Aviation Requirement: High power and energy per volume
5

Domestic off-grid / microgrid (e.g. balancing renewables) Requirement: Small scale, long lifetime
5 6 7 8

	1 Pumped hydropower	2 Compressed air energy storage	3 Thermal cycle	4 Flywheels / supercapaci-tors / SMES†	5 Hydrogen electrolyser / fuel cell	6 Lithium-ion batteries	7 Lead-acid batteries	8 Redox flow batteries
Capital cost	$ – $$	$ – $$	$ – $$	$$ – $$$	$$$	$$	$ – $$	$$
Cost per cycle								
Response time	Seconds – Minutes	Minutes	Seconds	Milliseconds – Minutes	Minutes	Milliseconds	Milliseconds	Milliseconds
Total deployment	3	2	1	1 / 2 / 1	3	2	3	1
Efficiency (%)	70 – 85	50 – 75	55 – 80	85 – 98	<40 (mature) Up to 66 (developing)	80 – 90	65 – 85	65 – 85
Daily self-discharge	>0.5%	>10%	0.5 – 1%	(100% / 5 – 20% / 10 – 15%)	~0%	~0%	~0.2%	~0%
In a nutshell	Affordable, but large and site-specific	Affordable, but large and site-specific	Potentially affordable, non site-specific	Fast response, but rapid discharge	Potential for long-term storage, currently expensive	High energy density, rapidly developing	Mature, but bulky and toxic materials	High number of cycles in lifetime, but bulky

Capital cost: ($/kWh for 1 – 8hr energy system): $ = 10 – 100, $$ = 100 – 1000, $$$ = 1000 – 10,000)

Cost per cycle: (including capital/cycle life, and operation, and maintenance. units $/kWh/cycle):
= < 0.01, = 0.01 – 0.10, = 0.10 – 1, = 1 – 10

Response time: Time a storage system requires to ramp up supply

Total deployment:
1 = less than 100 MW / 100MWh deployed
2 = 100 MW / 100 MWh to 10 GW / 10 GWh deployed
3 = more than 10 GW / 10 GWh deployed

Efficiency: Energy out divided by energy in

Daily self-discharge: Percentage of charge lost in device each day

* Other measures, such as increased interconnectivity, demand side management, thermal storage and dispatchable generation, also play a part in regulating the supply of electricity

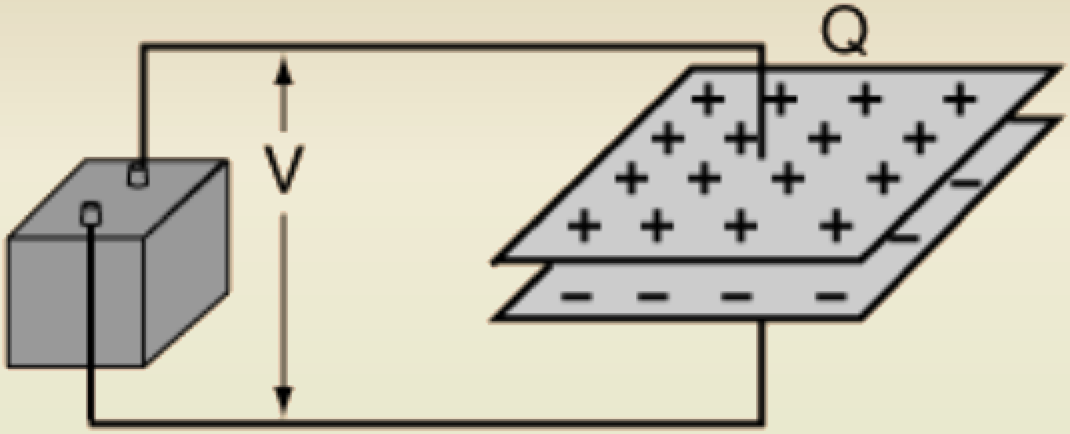
† Superconducting Magnetic Energy Storage

Grantham Institute
Climate Change and the Environment
An Institute of Imperial College London

Find out more at www.imperial.ac.uk/grantham/energy-storage

Energy storage

Capacitor



Capacitance

$$C = \frac{Q}{V}$$

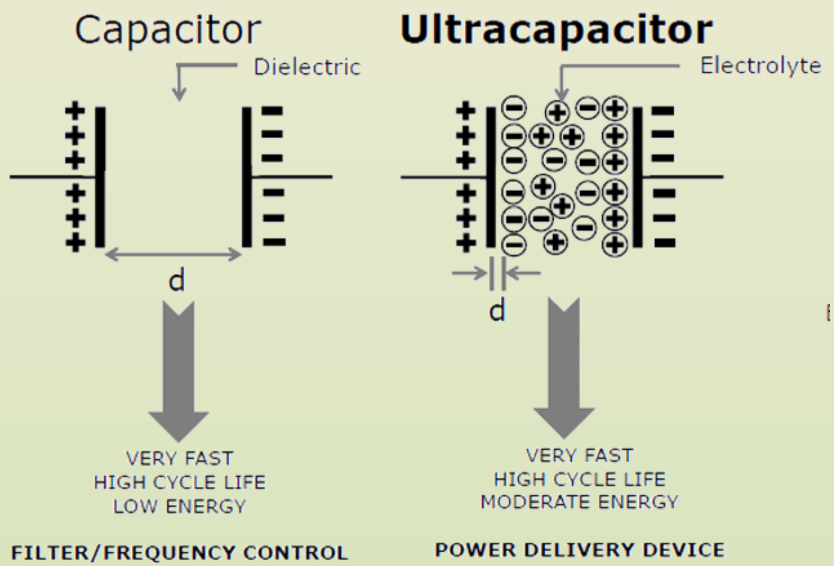
Energy is stored in the electric field

$$U = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}QV = \frac{1}{2}CV^2$$ Energy

$$\eta_E = \frac{energy}{volume} = \frac{1}{2}\varepsilon E^2$$ Energy density

Energy storage

Capacitor	Supercapacitor
• electrons are moved from one electrode and deposited on the other • charge is separated by a solid dielectric between the electrodes	• electrodes are separated by a liquid electrolyte rich in ions • when a voltage is applied to a supercap, these solvated ions form a double-layer of ions at each electrode (separated by the extremely thin non-conductive solvent) in what's known as the electrical double layer effect
• “small” capacitance (up to some thousand of μF) • high breakdown voltage (up to kV)	• huge capacitance (F or thousands of F) • low breakdown voltage (few V)



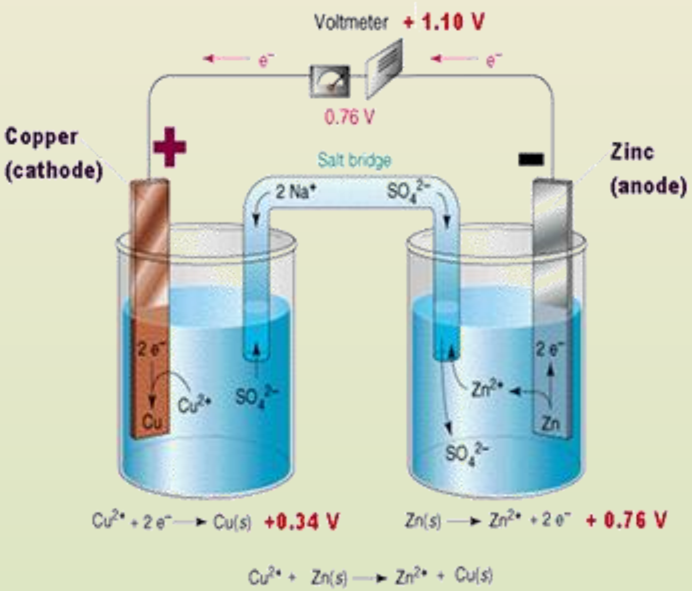
Energy storage

Batteries vs. Supercapacitors

Chemical Storage, high energy densities:
100's Wh/kg

Reactant diffusion, low power densities:
10 W/kg

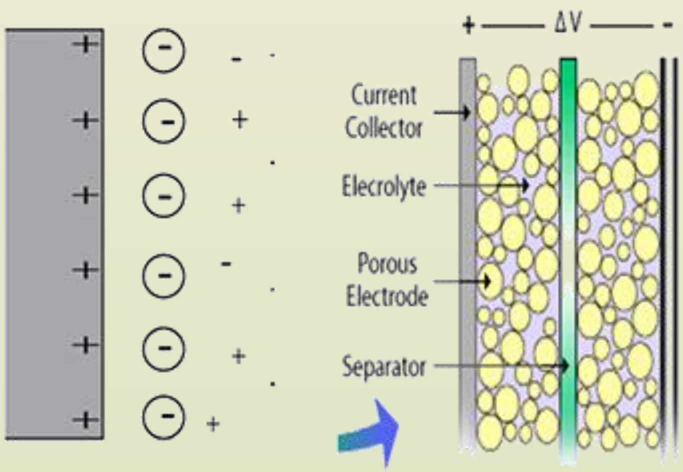
Low cycle life due to degradation



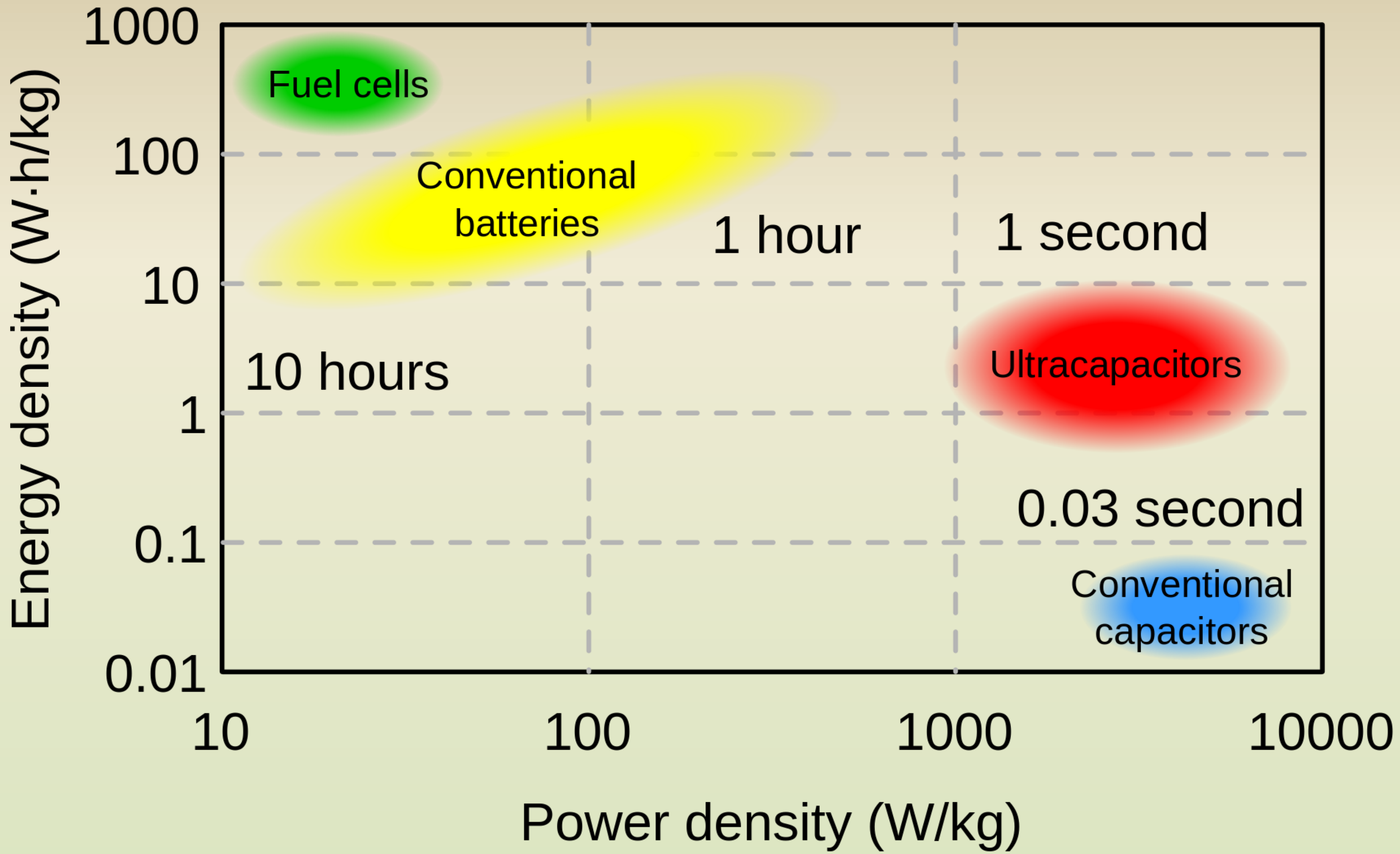
Surface Charge Storage, low energy densities:
1-10 Wh/kg

High power densities:
1 kW/kg

High cycle life (10^5 cycles)

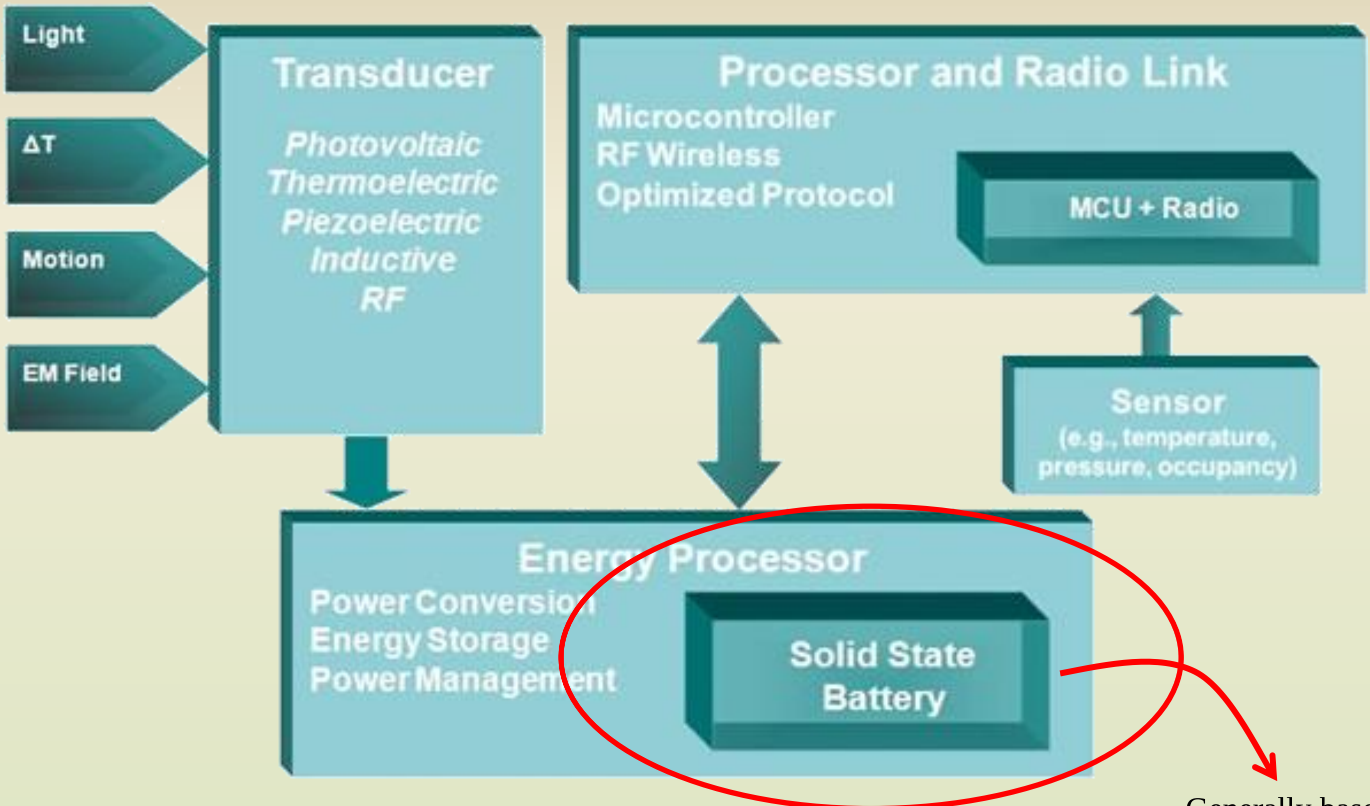


Energy storage



Energy storage

Energy Harvesting Perspectives

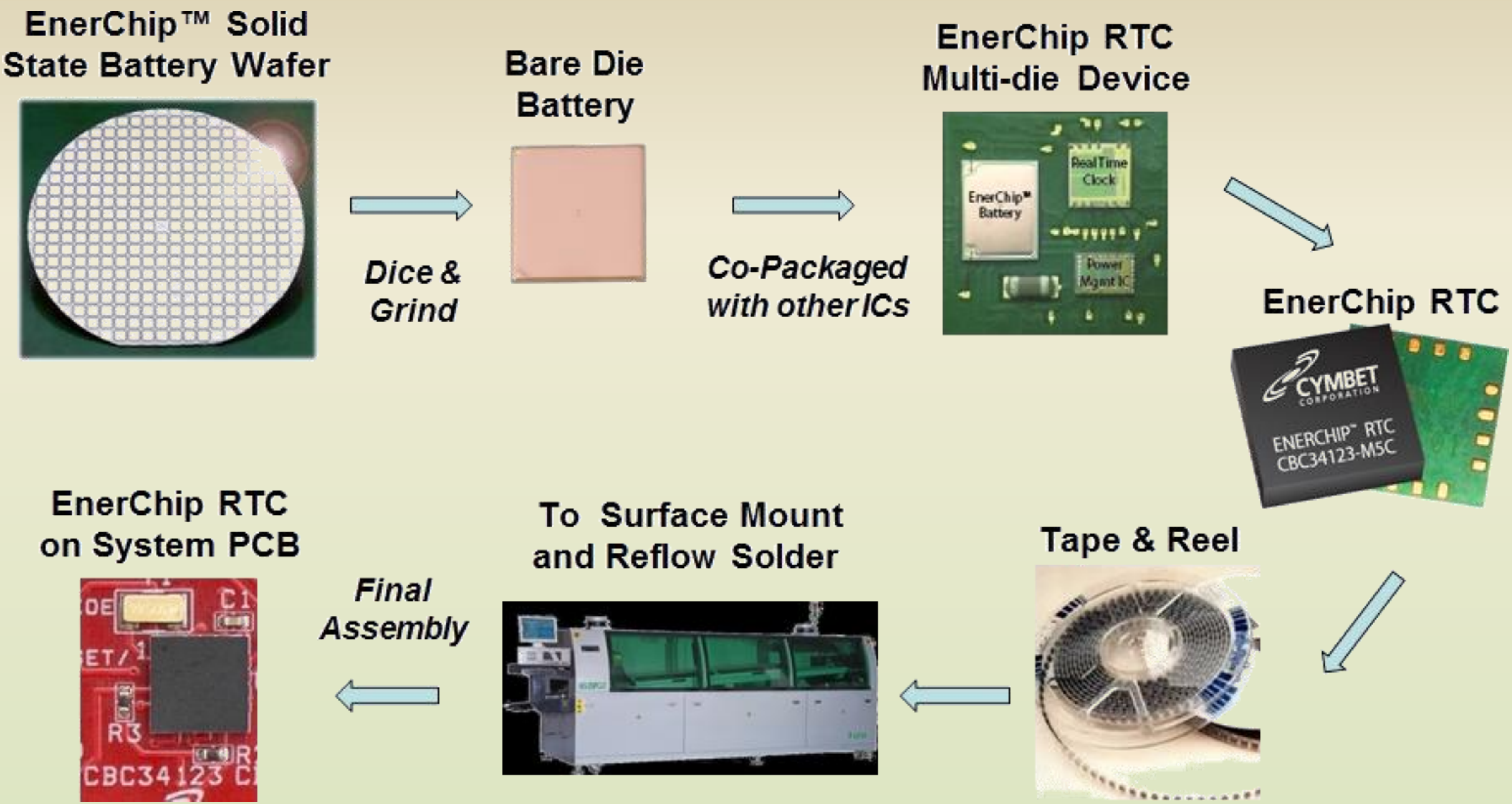


Generally based on:
- $LiCoO_2$ cathode
- LiPON ceramic electrolyte
- Lithium anode

http://www.cymbet.com/design-center/energy-harvesting-dc.php

Energy storage

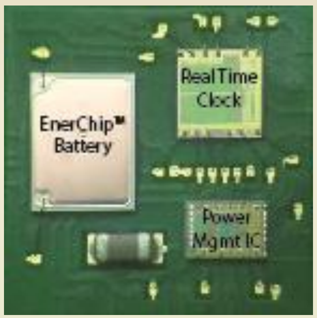
Rechargeable Solid State Battery Bare Die

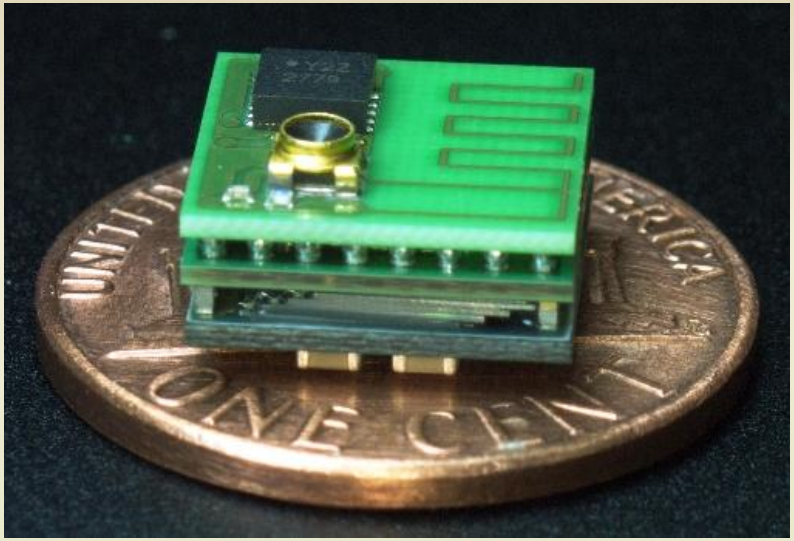


http://www.cymbet.com/about-us/technology.php

Energy storage

Rechargeable Solid State Battery Bare Die





- All Solid State Construction
- Thousands of Recharge Cycles
- Low Self-Discharge
- Fast Recharge
- Smallest Commercially Available: 1.7 x 2.25 x 0.175
- Flat Output Voltage Profile: nominal 3.8V
- Capacity (nominal): 5μAh
- Charging source: 4.1V, 15 minutes to 80%
- Charge/discharge cycles: >5000 at 10% discharge

http://www.cymbet.com/about-us/technology.php

Energy storage

Rechargeable Solid State Battery Bare Die

Preliminary **EnerChip™ CBC005 Energy Storage Device**

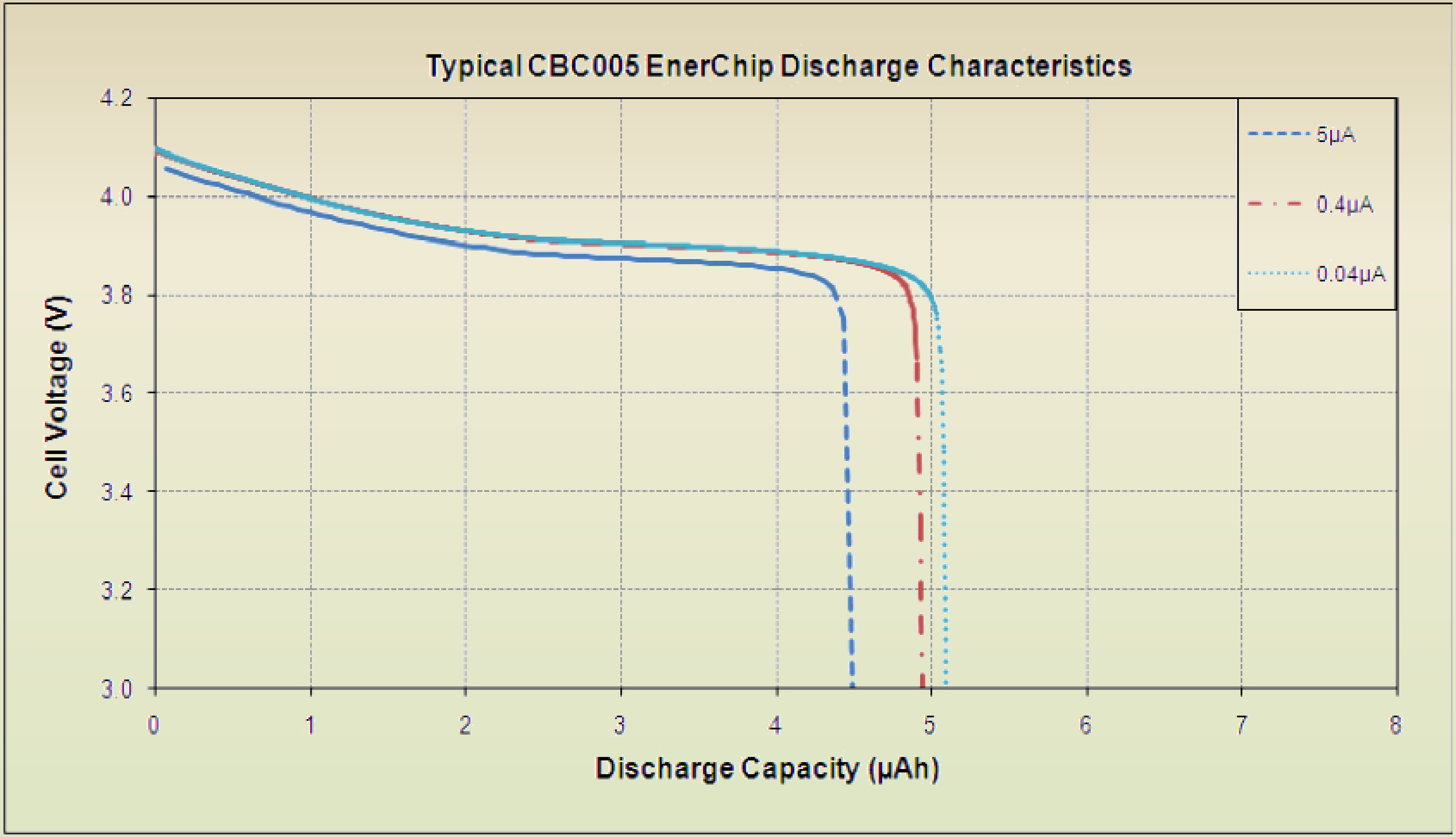
Operating Characteristics

Parameter		Condition	Min	Typical	Max	Units
Discharge Cutoff Voltage		25 °C	3.0[1]	-	-	V
Charge Voltage		25 °C	4.0[2]	4.1	4.2	V
Self-Discharge (average; 25 °C)		Non-recoverable	-	2.5	-	% per year
		Recoverable	-	1.5[3]	-	% per year
Operating Temperature		-	-20	-	+70	°C
Storage Temperature		-	-40	-	+125[4]	°C
Cell Resistance (25 °C)		Charge cycle 2	-	7	11	KΩ
		Charge cycle 1000	-	31	48	
Recharge Cycles (to 80% of rated capacity; 4.1V charge voltage)	25 °C	10% depth-of-discharge	5000	-	-	cycles
		50% depth-of discharge	1000	-	-	cycles
	40 °C	10% depth-of-discharge	2500	-	-	cycles
		50% depth-of-discharge	500	-	-	cycles
Recharge Time (to 80% of rated capacity; 4.1V charge voltage)		Charge cycle 2	-	11	22	minutes
		Charge cycle 1000	-	45	70	
Discharge Capacity		400nA discharge; 25 °C	5.0	-	-	µAh

http://www.cymbet.com/pdfs/DS-72-30.pdf

Energy storage

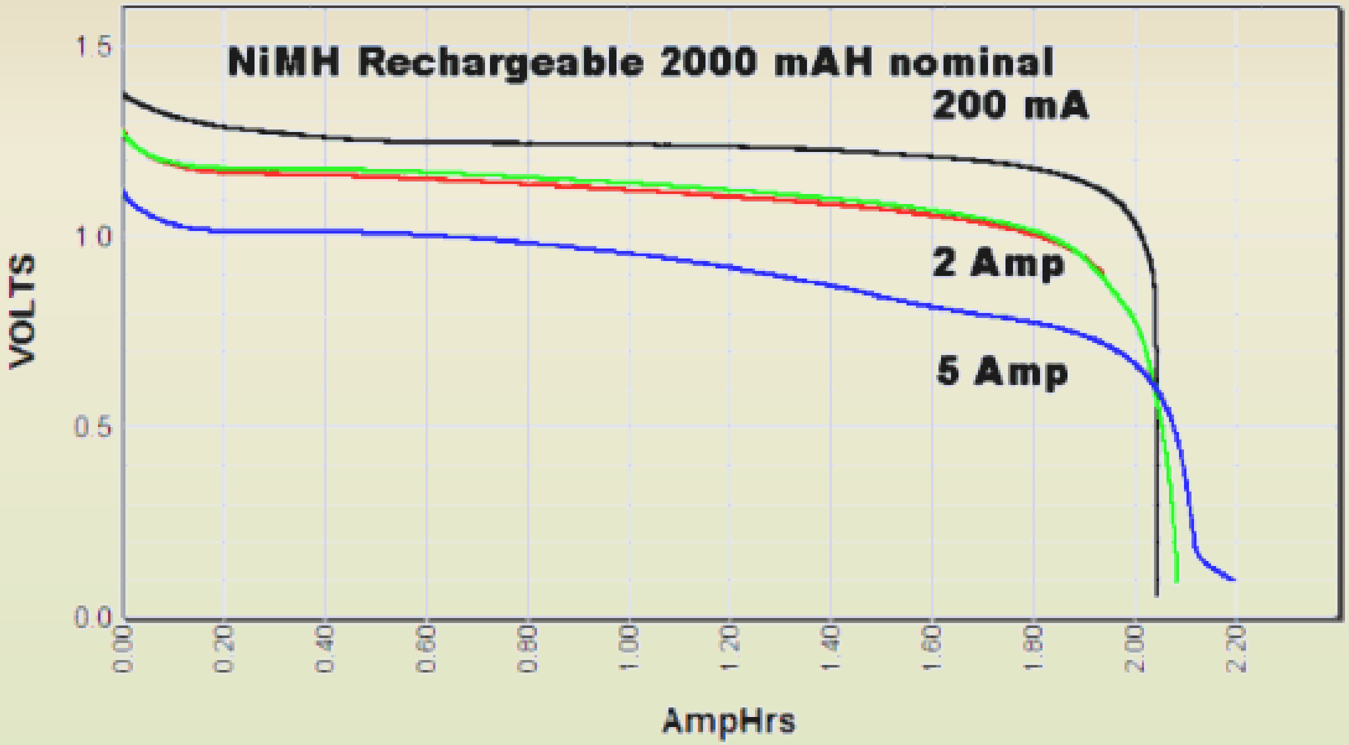
Rechargeable Solid State Battery Bare Die



http://www.cymbet.com/pdfs/DS-72-30.pdf

Energy storage

Discharge tests of AA NiMH battery at different rate



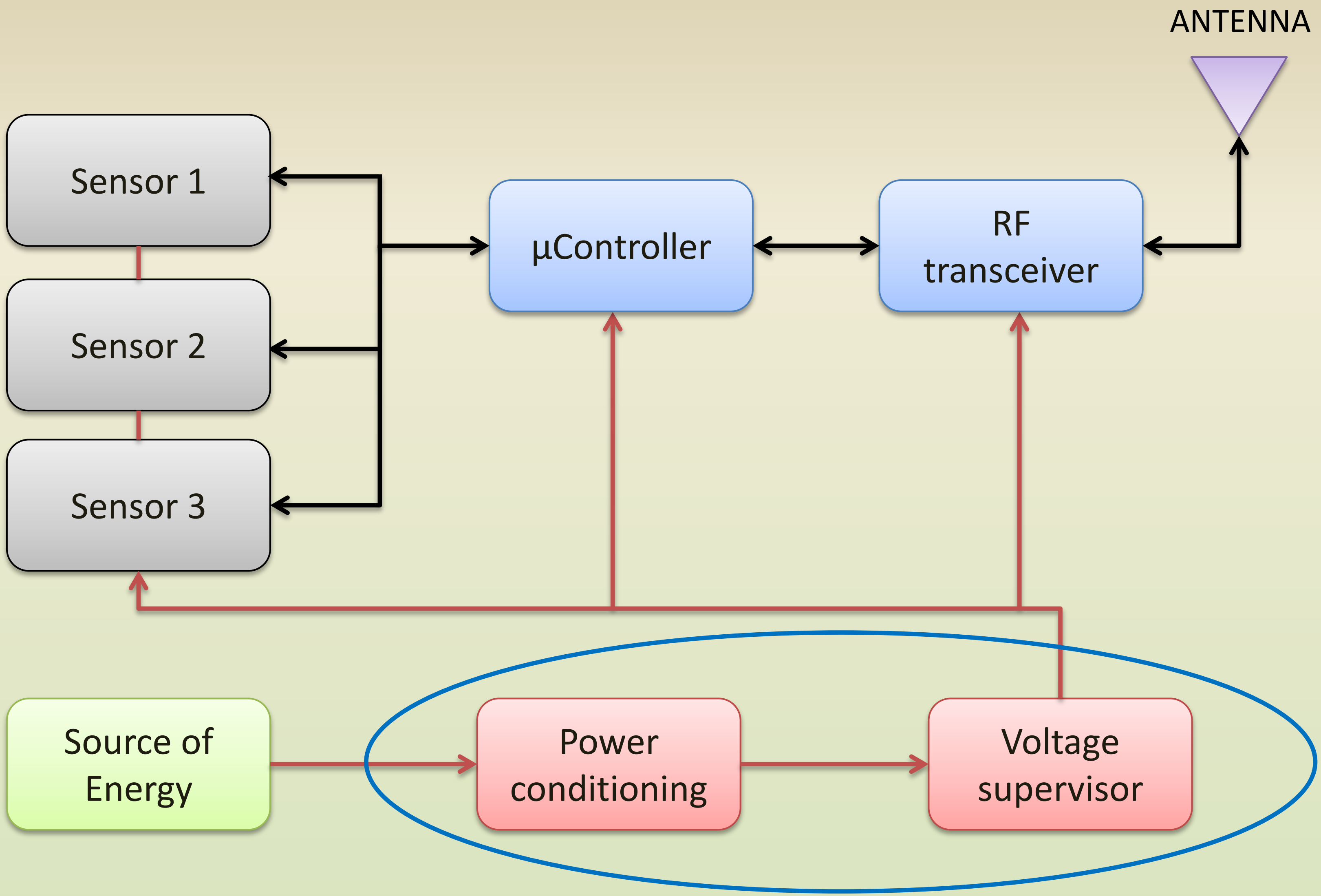
https://www.powerstream.com/AA-tests.htm

Outline

- *Introduction*
- *Electrical impedance matching*
- *Electrical energy conversion*
- *Energy storage*
- *Power management*

Power management

Typical wireless sensor node



Power management

CASE STUDY: TIME DISTRIBUTION OF THE OPERATING MODES

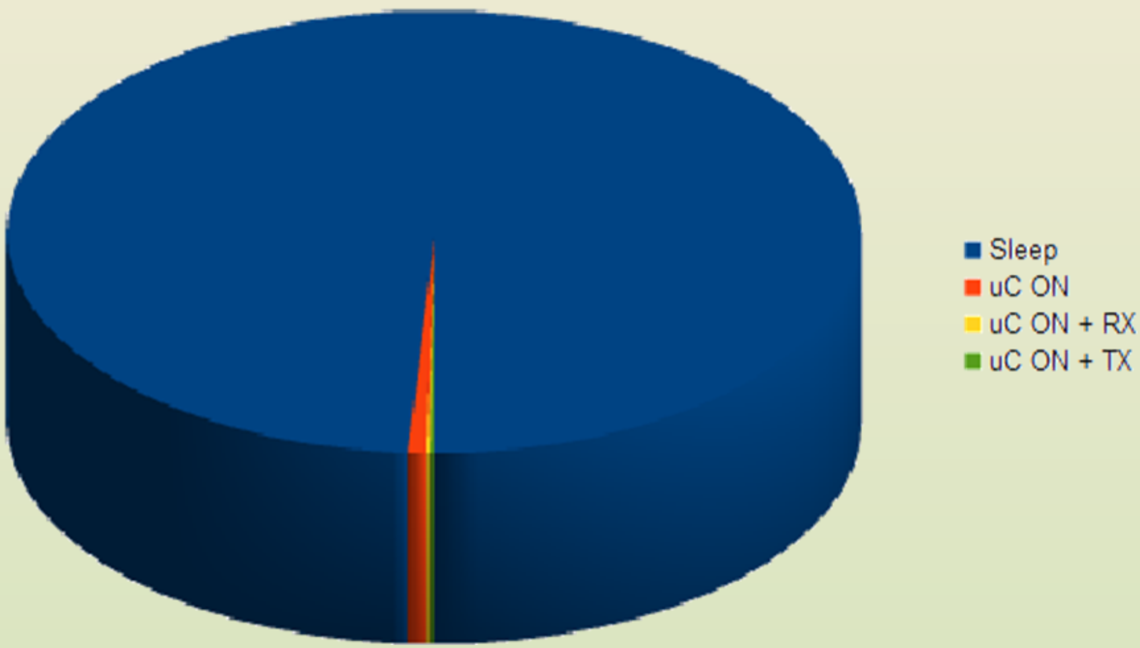
Period: 1 s

µController: sleep mode 0,990 s

µController: active mode 0,007 s

µController: active mode + RX 0,001 s

µController: active mode + TX 0,002 s



Power management

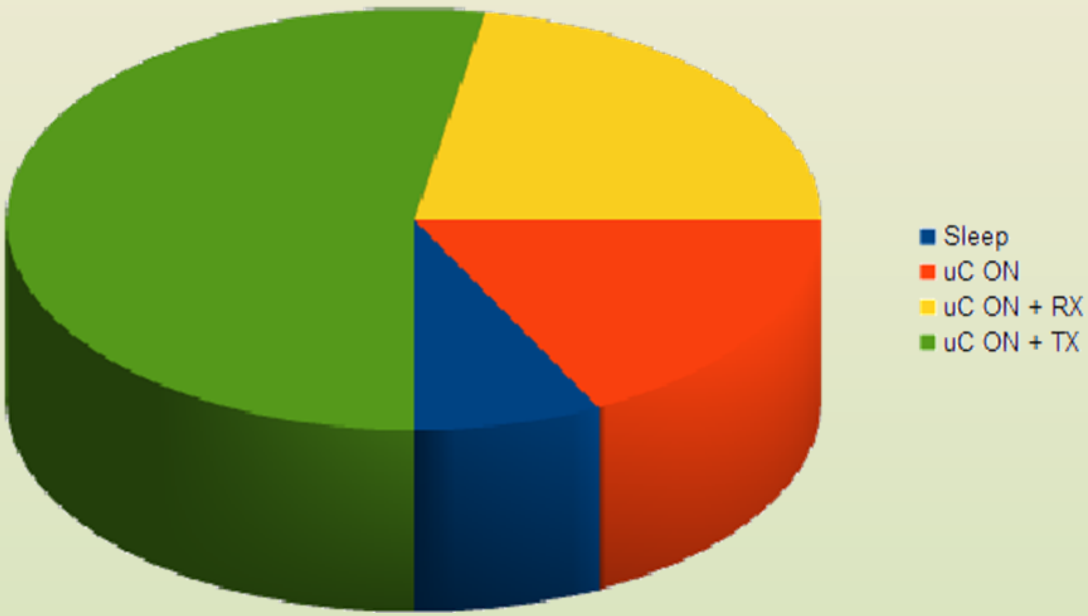
ENERGY CONSUMPTION vs OPERATING MODES

$$P_{TOT} = P_{\mu Controller} + P_{RX} + P_{TX} + P_{SUPERVISOR}$$

$$P_{\mu Controller} \propto I_{\mu Controller} = 2{,}4\, mA\, @\, 16\, MHz\, ,\, 270\, nA\, D - Sleep + WDT$$

$$P_{TX} \propto I_{TX} = 23\, mA\, @\, 0\, dBm \qquad P_{RX} \propto I_{RX} = 19\, mA$$

$$P_{SUPERVISOR} \propto I_{SUPERVISOR} = 7\, \mu A$$



Power management

ENERGY CONSUMPTION vs OPERATING MODES

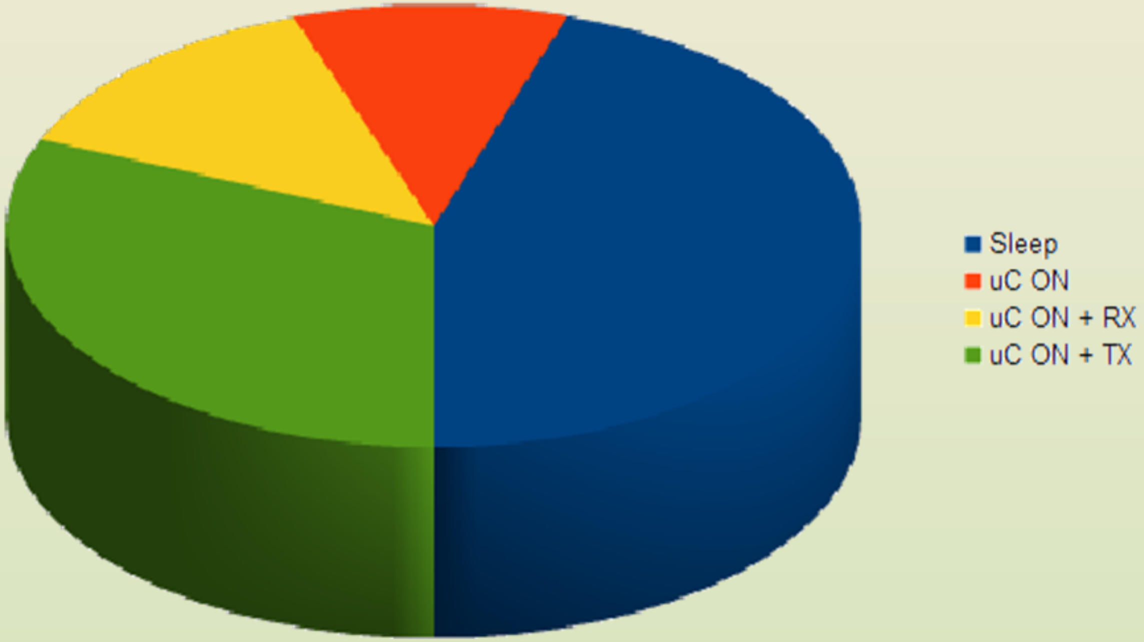
Period: 10 s

µController: sleep mode 9,990 s

µController: active mode 0,007 s

µController: active mode + RX 0,001 s

µController: active mode + TX 0,002 s



Power management

ENERGY CONSUMPTION vs OPERATING MODES

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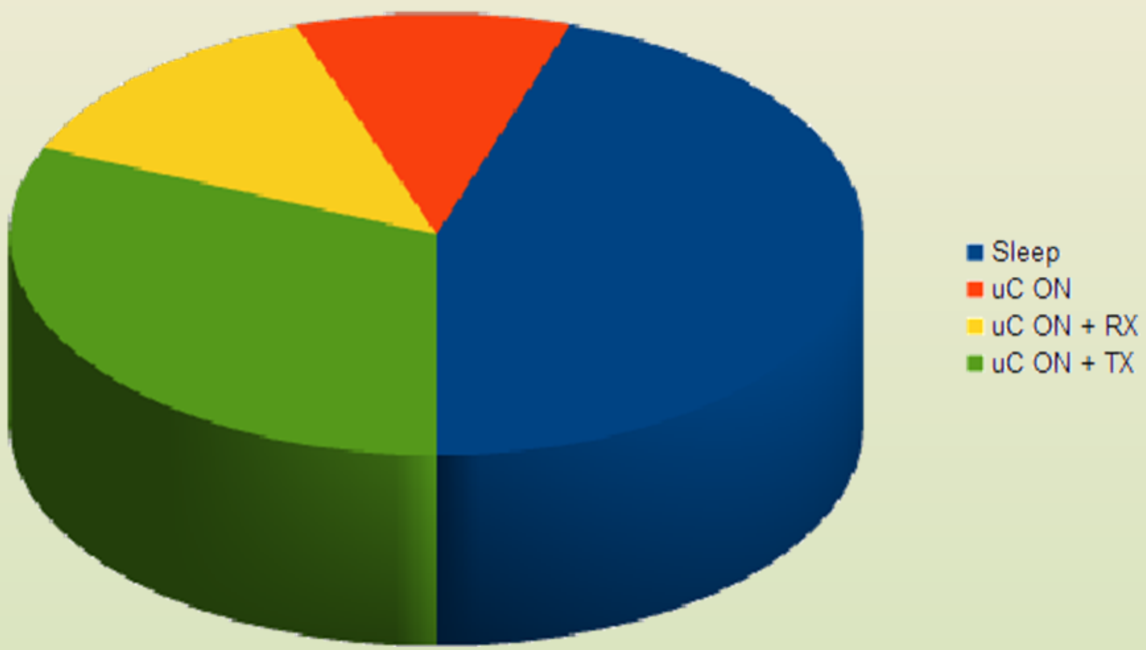


Power management

Design rules:

Rule #1: there not exist one optimal solution for all the applications!

Rule #2: try to minimize the energy loss during power regulation!

Rule #3: not always the highest efficiency is the optimal design criteria.
Probably the “highest power conversion ratio” is a better one!

Power management

Voltage regulator

Linear (resistive)

- Simple/low cost solutions
- Low noise/low ripple applications
- Fast transient applications
- Low dropout applications
- Heavy

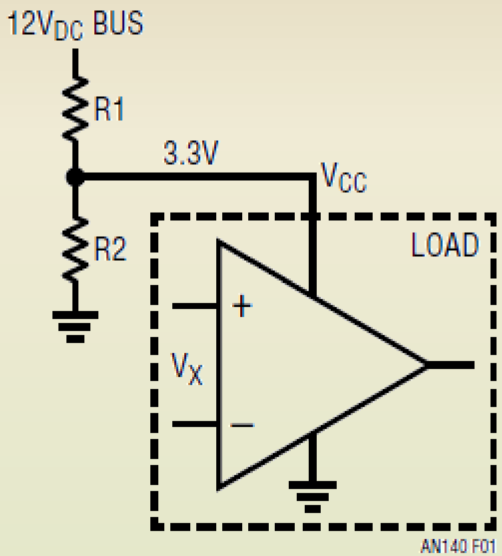
Switching

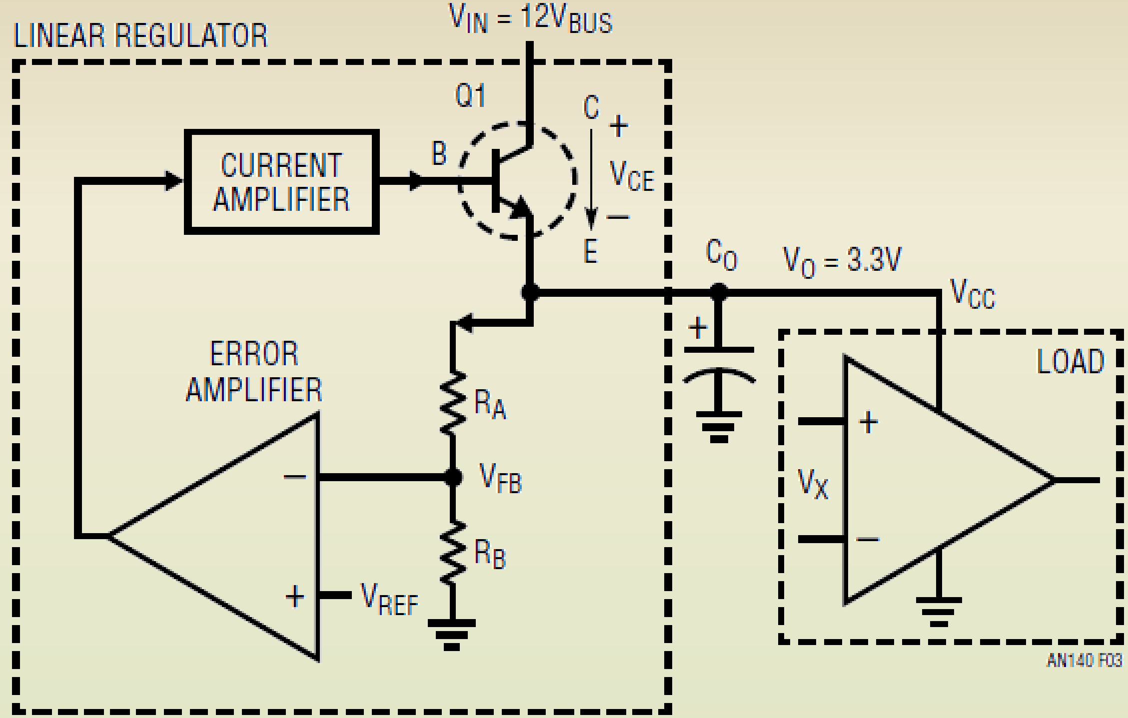
- Higher efficiency than linear regulators
- Lower heat produces
- High to low and low to gigh voltage conversion
- Less board area
- Light

http://cds.linear.com/docs/en/application-note/AN140fa.pdf

Power management

Linear voltage regulators



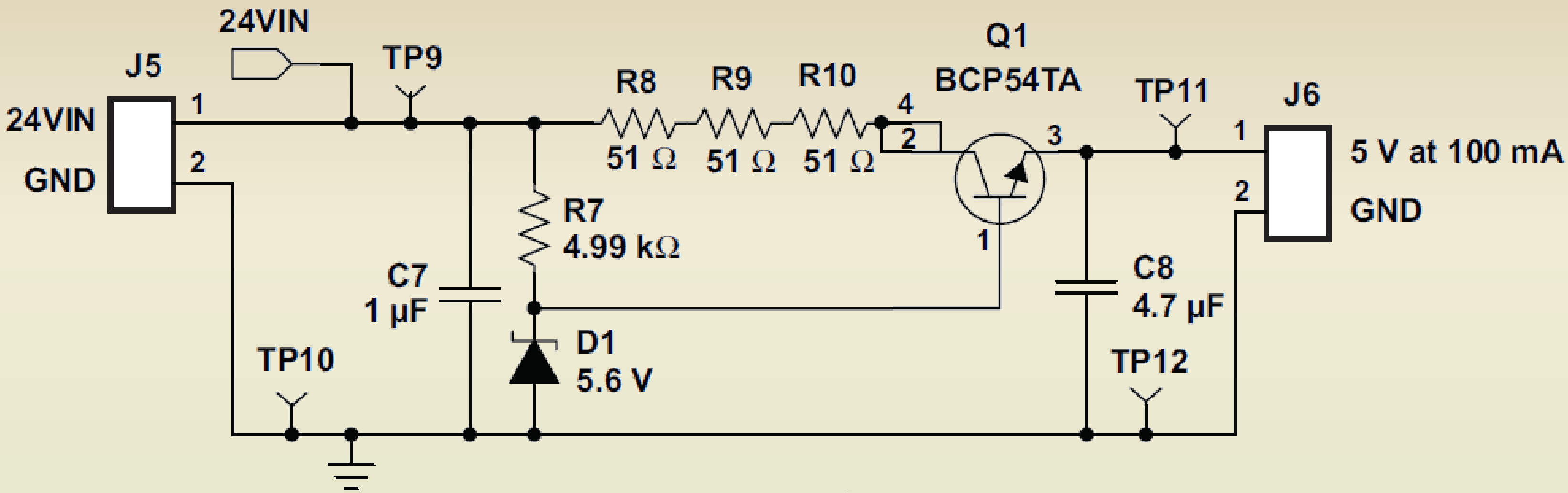


A linear regulator implements a variable resistor to regulate the otput voltage

http://cds.linear.com/docs/en/application-note/AN140fa.pdf

Power management

Linear voltage regulators



Dissipated power

$$P_D = (V_{IN} - V_{OUT})I_{LOAD}$$

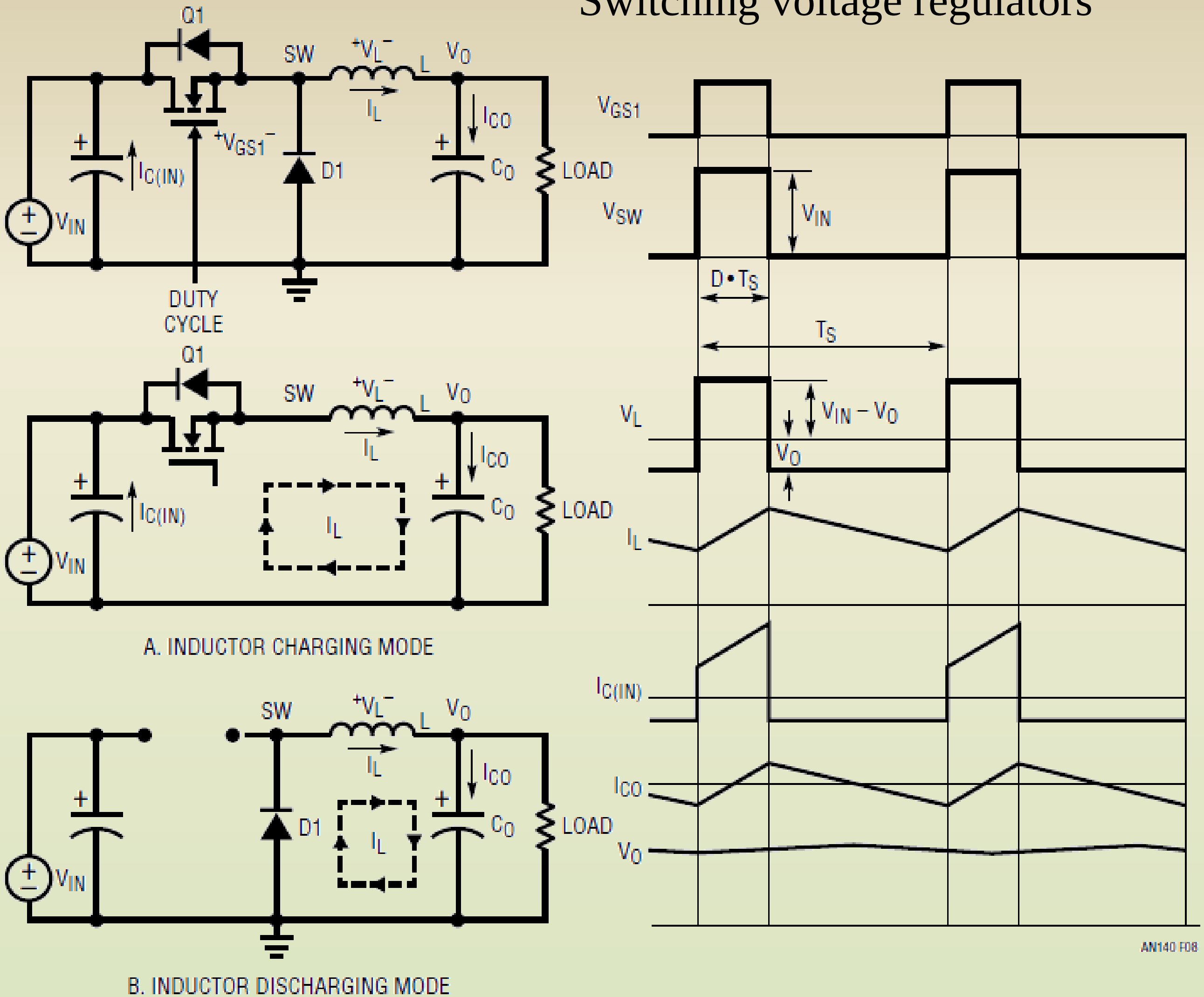
Efficiency

$$\eta = \frac{P_{OUT}}{P_{IN}} \cong \frac{V_{OUT}}{V_{IN}}$$

http://www.ti.com/lit/an/slyt527/slyt527.pdf

Power management

Switching voltage regulators



$$V_{OUT} = AVG[V_{SW}] =$$

$$= \frac{T_{ON}}{T_S} V_{IN} = \delta \cdot V_{IN}$$

Duty cycle

http://cds.linear.com/docs/en/application-note/AN140fa.pdf

Power management

The calculation of switching related losses is usually not easy.

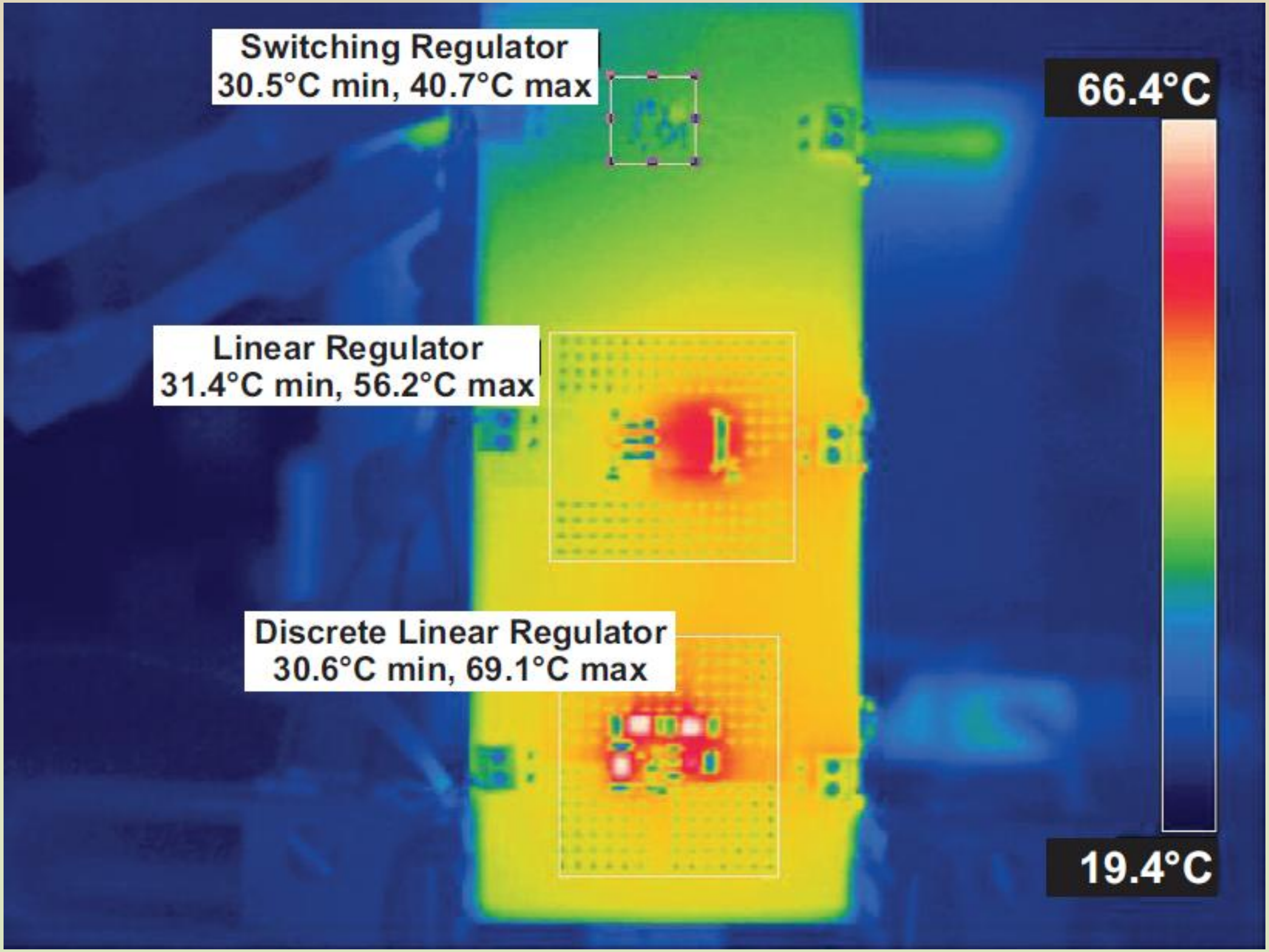
- DC conduction losses (transistor, diode, inductor)
- AC switching losses (switch ON and OFF time)
- Inductor core losses (frequency depending)
- Other losses (control circuitry…)

The switching related losses are proportional to switching frequency *fs*.

http://cds.linear.com/docs/en/application-note/AN140fa.pdf

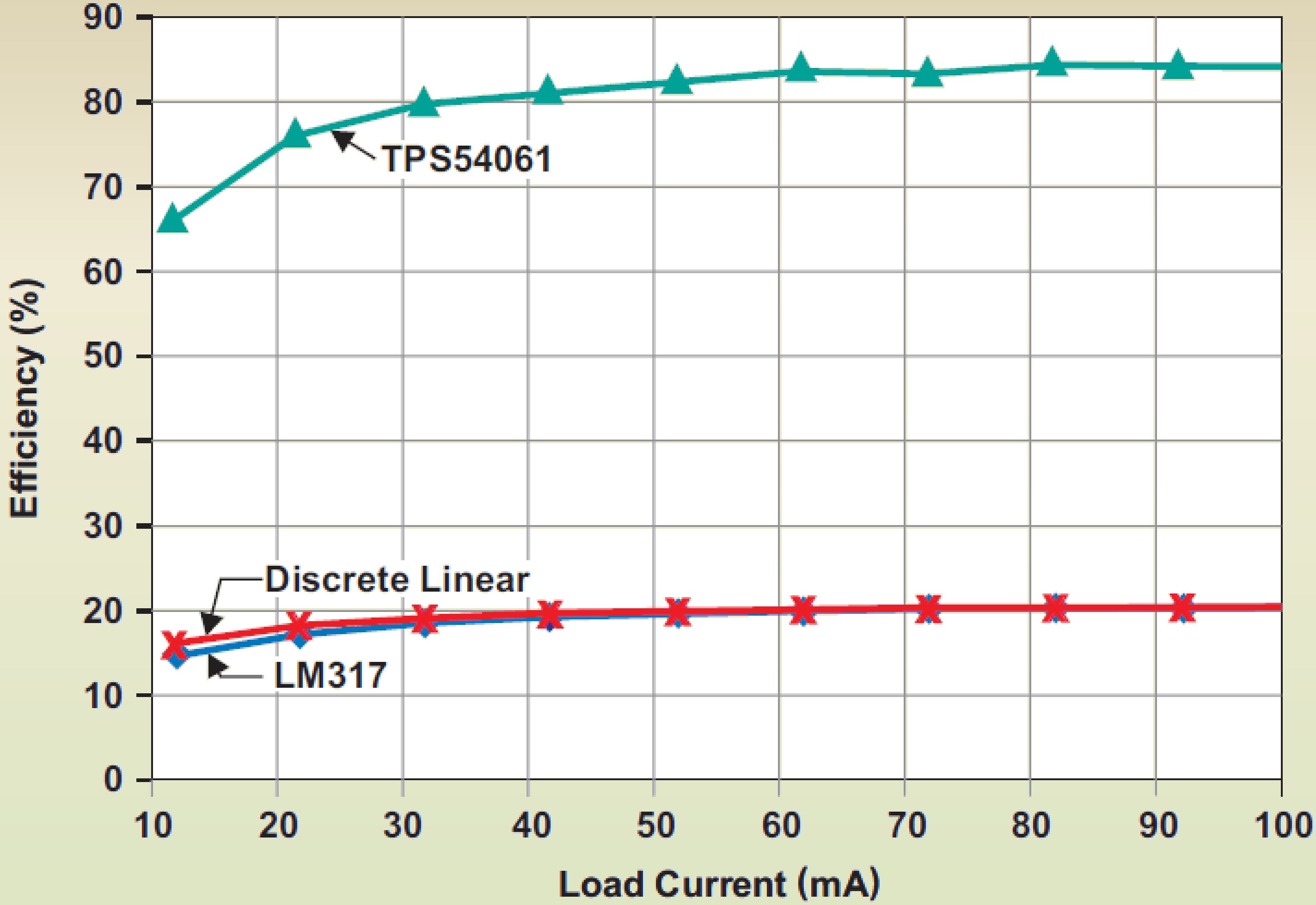
Power management

Linear vs Switching voltage regulators



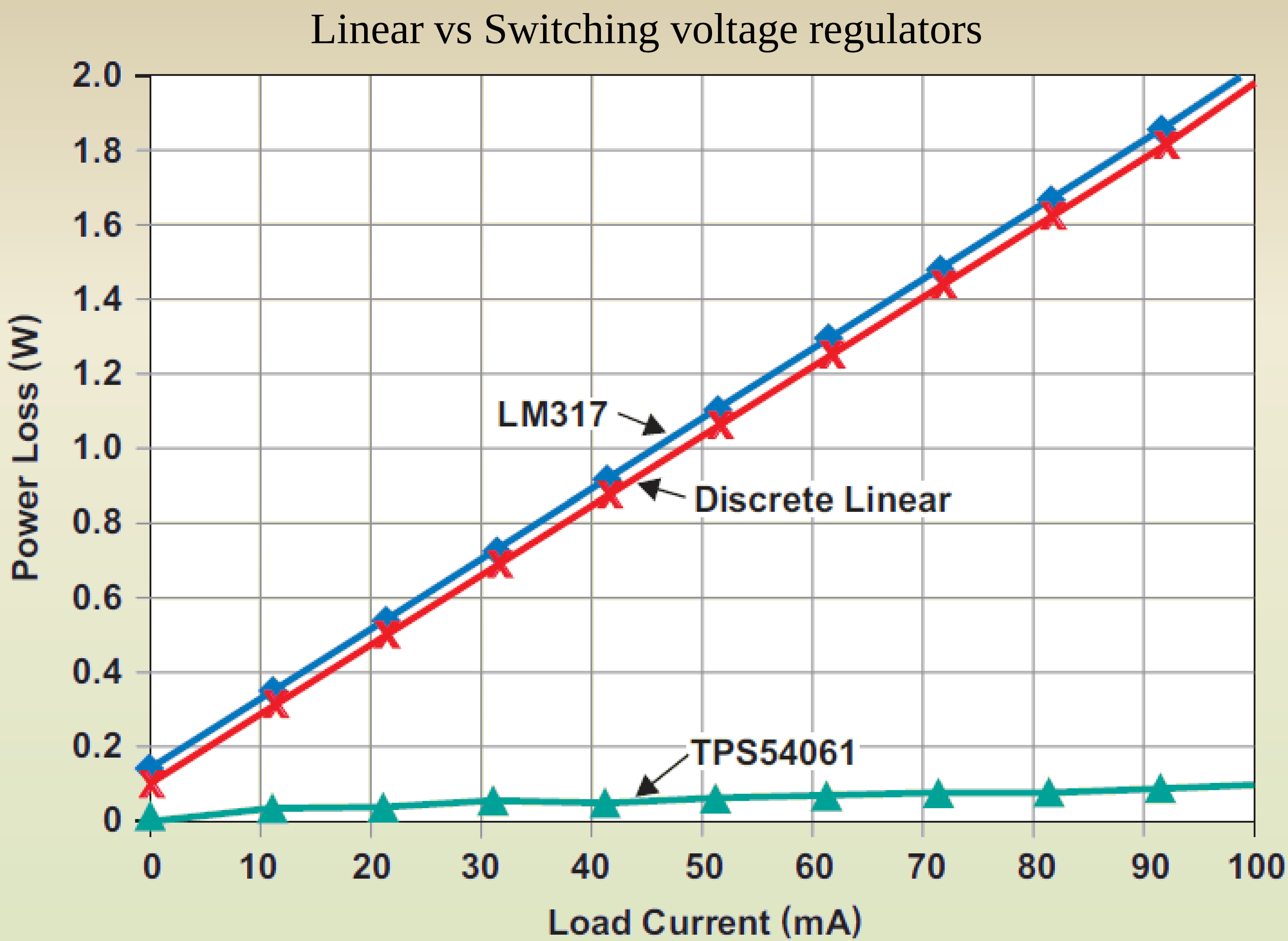
Power management

Linear vs Switching voltage regulators



http://www.ti.com/lit/an/slyt527/slyt527.pdf

Power management



http://www.ti.com/lit/an/slyt527/slyt527.pdf


Thank you!