Power Management in Energy Harvesting Power Supplies

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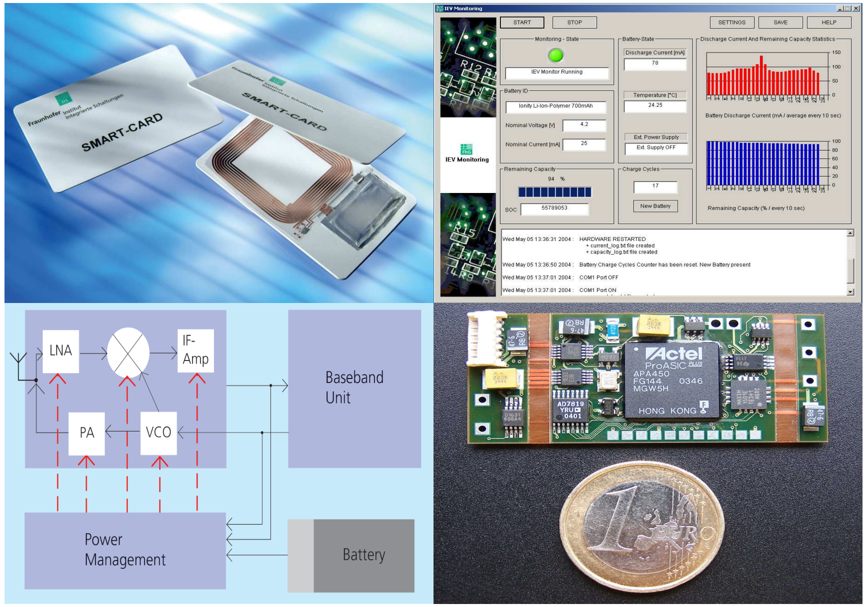
Fraunhofer IIS: Department Power Efficient Systems

Technologies for Terminal Devices

Energy Systems



- Power Management
- Battery Management
- Battery Monitoring
- Energy Transmission
- Energy Harvesting

- www.iis.fraunhofer.de/ec/power
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3rd Fraunhofer Symposium Micro Energy Technology

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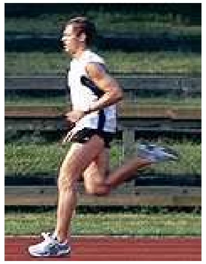
Agenda

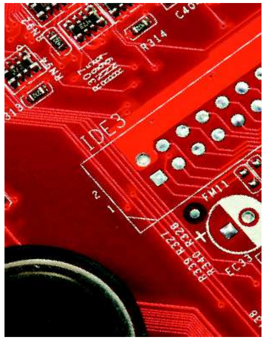
- Introduction
- Energy Harvesting Sources
- Energy Harvesting Transducers
- Semiconductor Roadmap (ITRS)
- Low-voltage DC-DC Converter
- Discontinuous Mode
- Maximum Power Point Tracker
- Summary and Conclusions

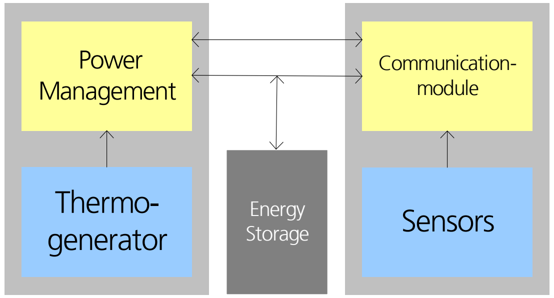
Introduction



- power consumption of electronic circuits and systems is decreasing more and more
- efficiency of energy transducers (e.g. thermo-generators [TEGs], piezoelectric modules, solar cells) is being further optimized
- energy from the environment to supply electronic devices: '*Energy Harvesting*'
- application devices: sensors, wireless transceivers or displays
- application fields: structural health monitoring, medicine, consumer products, automotive, logistics, security, household, etc.

Introduction





- key role of power management as interface between transducer and load

- duties of power management :
  - matching voltage and current profile of transducer and load
  - supply voltage regulation
  - minimization of power consumption
  - management of required storage devices

- power management is the *<u>'enabling technology'</u>* for energy harvesting power supplies

- improvement of the power management >> increase of application areas and development of new application fields

Energy Harvesting Sources - Vibration

- peak acceleration: 0.1…10 m/s^2 (about 0.01…1 g)
- frequency range: 60…385 Hz

Vibration Source	Peak Acc. (m/s^2)	Frequency of Peak (Hz)
Base of 5 HP 3-axis machine tool with 36” bed	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just after door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2 – 1.5	60
Wooden deck with people walking	1.3	385
Breadmaker	1.03	121
External windows (size 2 ft X 3 ft) next to a busy street	0.7	100
Notebook computer while CD is being read	0.6	75
Washing Machine	0.5	109
Second story floor of a wood frame office building	0.2	100
Refrigerator	0.1	240

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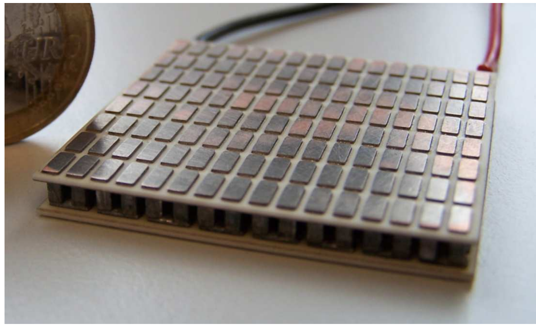
Energy Harvesting Transducers - Vibration

Perpetuum

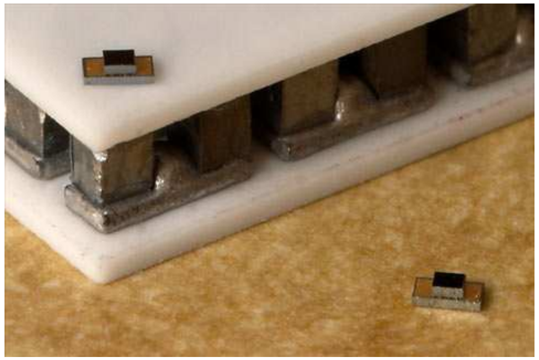
Ferro Solutions

Company	Principle	Power output	Volume
Perpetuum PMG17	Electro-dynamic	1 mW @ 0.025 g rms, 2 Hz BW; 45 mW @ 1 g rms, 15 Hz BW;	d=55 mm h=55 mm
Perpetuum PMG27-17	Electro-dynamic	2 mW @ 25 mg, 17.2 Hz	d=53 mm h=53mm
Ferro Solutions VEH360	Electro-dynamic	0.8 mW @ 20 mg, 60 Hz; 10.8 mW @ 100 mg, 60 Hz; 50% in 3 Hz	d=66 mm h=39 mm
HSG-IMIT	Electro-static	1 µW – 50 µ W	5 * 6 mm
HSG-IMIT	Piezo-electric	320 µW @ 220 Hz, 5 µm	46*20*10 mm
HSG-IMIT	Electro-dynamic	10 µW – 100 mW	1 cm^3 – 1 dm^3
Midé PEH25W	Piezo-electric	6 mW @ 1 g rms, 30 Hz 0.8 mW @ 1 g rms, 100 Hz	92*44.5*9.9 mm
Midé PEH20W	Piezo-electric	8 mW @ 1 g rms, 50 Hz; 1.8 mW @ 1 g rms, 150 Hz	92*44.5*9.9 mm

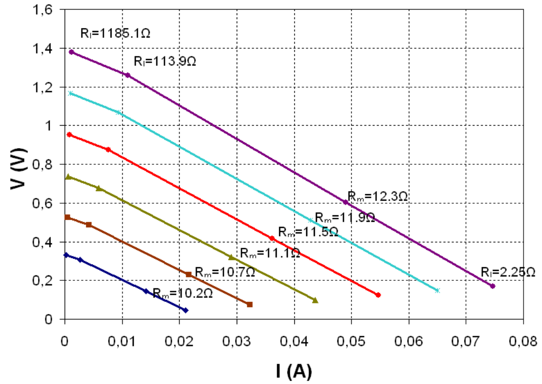
Energy Harvesting Transducers - Thermal Gradient



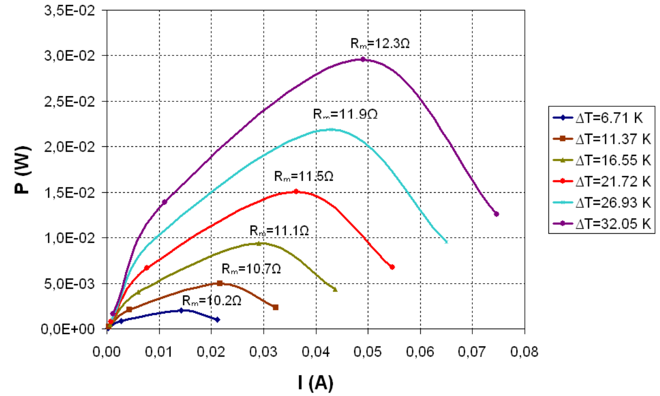
Peltron



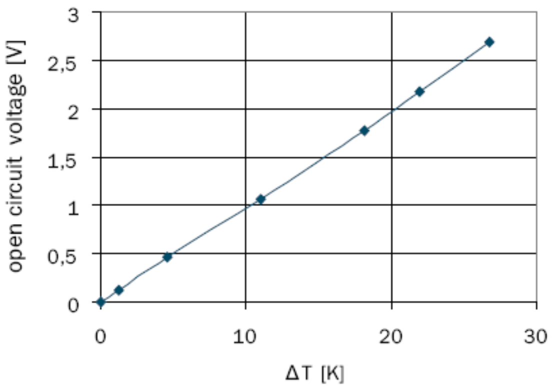
Fraunhofer IPM, Micropelt

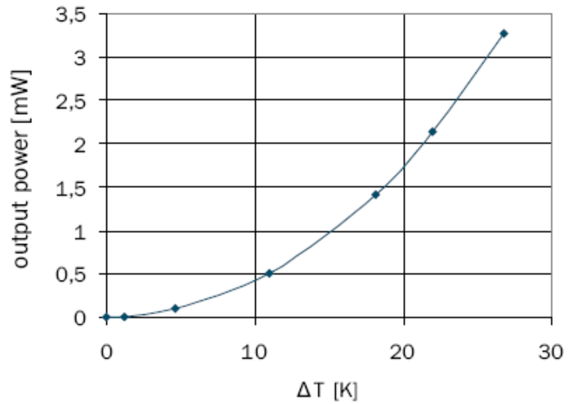


Voltage versus ΔT



Maximum electrical output power





International Technology Roadmap for Semiconductor (ITRS)

- supply voltages and currents are decreasing >> support for Energy Harvesting
- 2022 still 0.7 V >> need for dc-dc up conversion
- device is shrunk in geometrical size (Tox, L) >> leakage currents will increase

Year of Production	*2016*	*2017*	*2018*	*2019*	*2020*	*2021*	*2022*
DRAM ½ Pitch (nm) (contacted)	*22*	*20*	*18*	*16*	*14*	*13*	*11*
Performance RF/Analog [1]							
Supply voltage (V) [2]	0.8	0.8	0.8	0.8	0.75	0.75	0.7
T_{ox} (nm) [2]	1.1	1.1	1	1	0.9	0.9	0.8
Gate Length (nm) [2]	16	14	13	12	11	10	10
g_m/g_{ds} at $5 \cdot L_{min\text{-}digital}$ [3]	30	30	30	30	30	30	30
1/f-noise ($\mu V^2 \cdot \mu m^2/Hz$) [4]	50	50	40	40	30	30	30
σ V_{th} matching (mV·µm) [5]	4	4	4	4	3	4	5
I_{ds} (µA/µm) [6]	4	3	3	3	2	2	2
Peak F_t (GHz) [7]	550	630	670	730	790	870	870
Peak F_{max} (GHz) [8]	710	820	880	960	1050	1160	1160
NF_{min} (dB) [9]	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Precision Analog/RF Driver [1]							
Supply voltage (V)	1.8	1.8	1.8	1.5	1.5	1.5	1.5
T_{ox} (nm) [10]	3	3	3	2.6	2.6	2.6	2.6
Gate Length (nm) [10]	180	180	180	130	130	130	130
g_m/g_{ds} at $10 \cdot L_{min\text{-}digital}$ [11]	160	160	160	110	110	110	110
1/f Noise ($\mu V^2 \cdot \mu m^2/Hz$) [4]	180	180	180	135	135	135	135
σ V_{th} matching (mV·µm) [5]	6	6	6	5	5	5	5
Peak F_t (GHz) [7]	50	50	50	70	70	70	70
Peak F_{max} (GHz) [8]	90	90	90	120	120	120	120

Manufacturable solutions exist, and are being optimized (white)
Manufacturable solutions are known (yellow)
Interim solutions are known (yellow/orange striped)
Manufacturable solutions are NOT known (red)

Requirements

- due to properties of energy sources, transducers and semiconductor technology development:
  - minimum start-up / supply voltages
  - zero-power standby-modes
  - minimum leakage currents
  - maximum efficiency at small loads / load range

- first solutions:
  - low-voltage dc-dc converter
  - discontinuous mode
  - maximum power point (MPP) tracker

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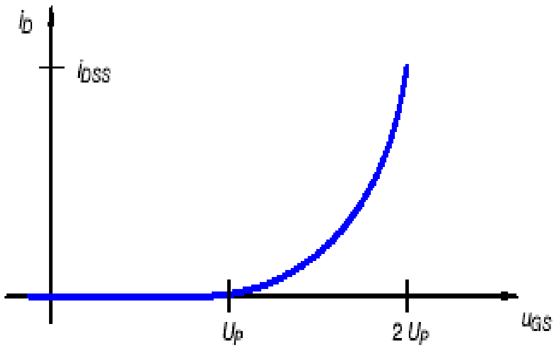
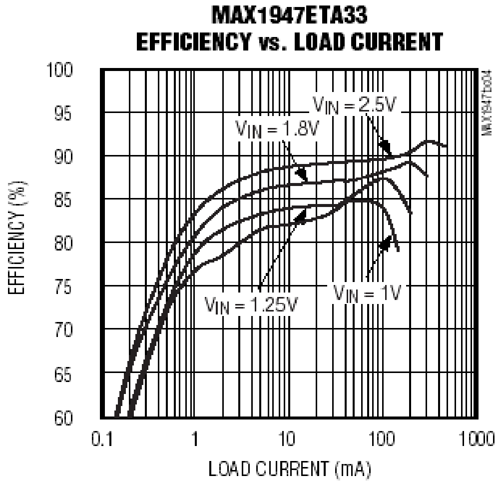
Low Voltage DC-DC Converter

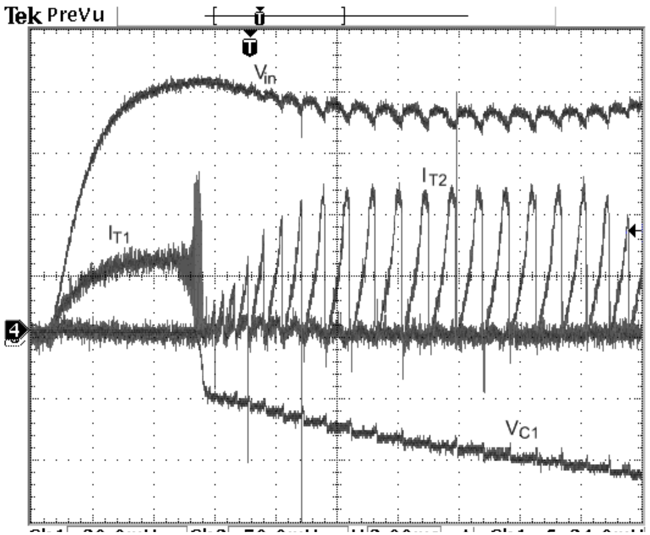


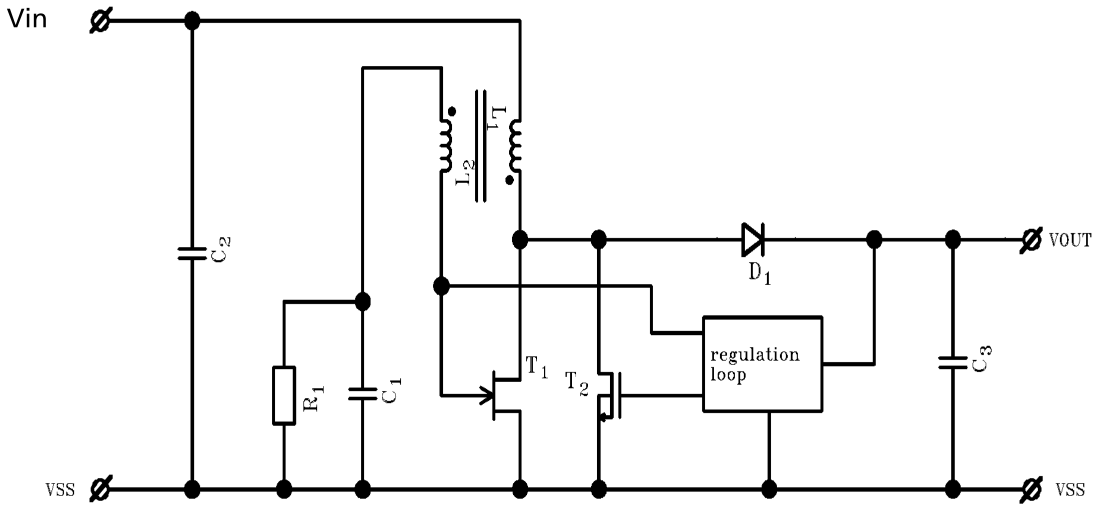


- threshold voltages of semiconductor technologies are scaled down
- nevertheless: gap between output of energy transducers and minimum input of voltage converters (e.g. 0.7 V)
- thermo-generators: about 50 mV per Kelvin
- solar/fuel cells: about 0.5 V
- to use minimum amounts of energy (small temperature gradients, little illumination) low-voltage dc-dc up converters
- special low-threshold transistors or dedicated dc-dc converters architectures

Low-voltage DC-DC Converter

- coupled inductor dc-dc converter starts with 20 mV due to JFET
- turns ration L1:L2=1:17





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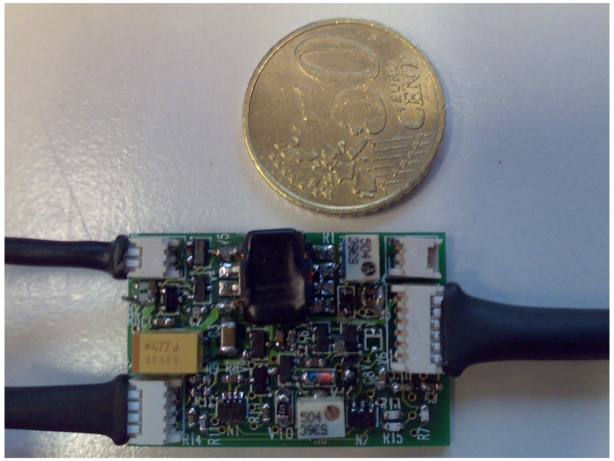
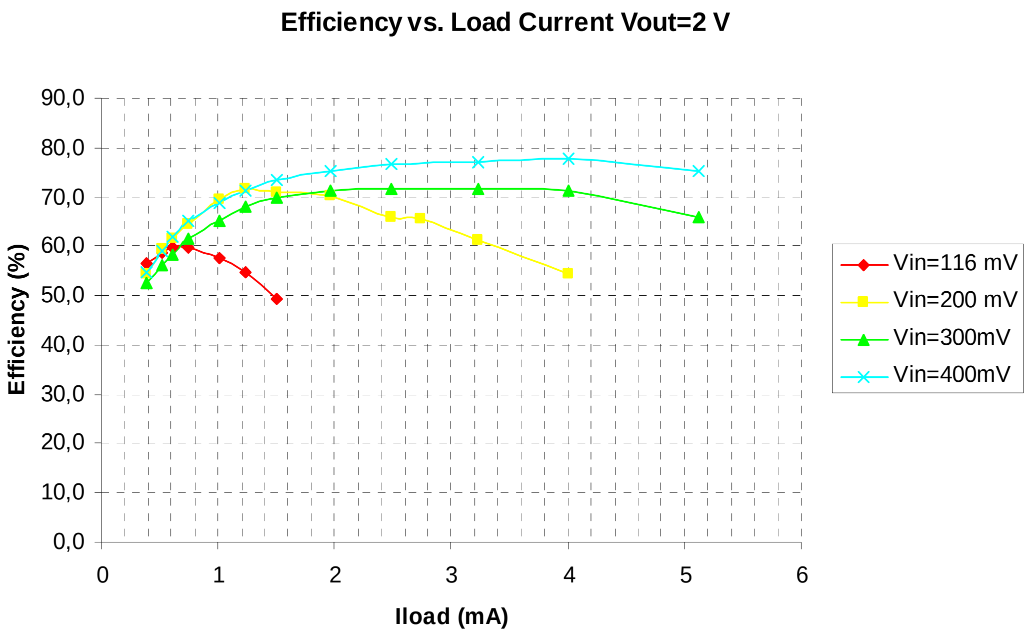
Low-voltage DC-DC Converter

- efficiency between 50 and 78 %
- depending on input voltage and load current





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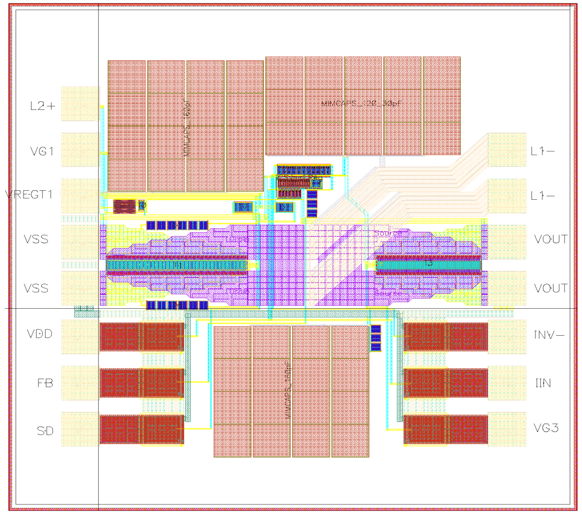
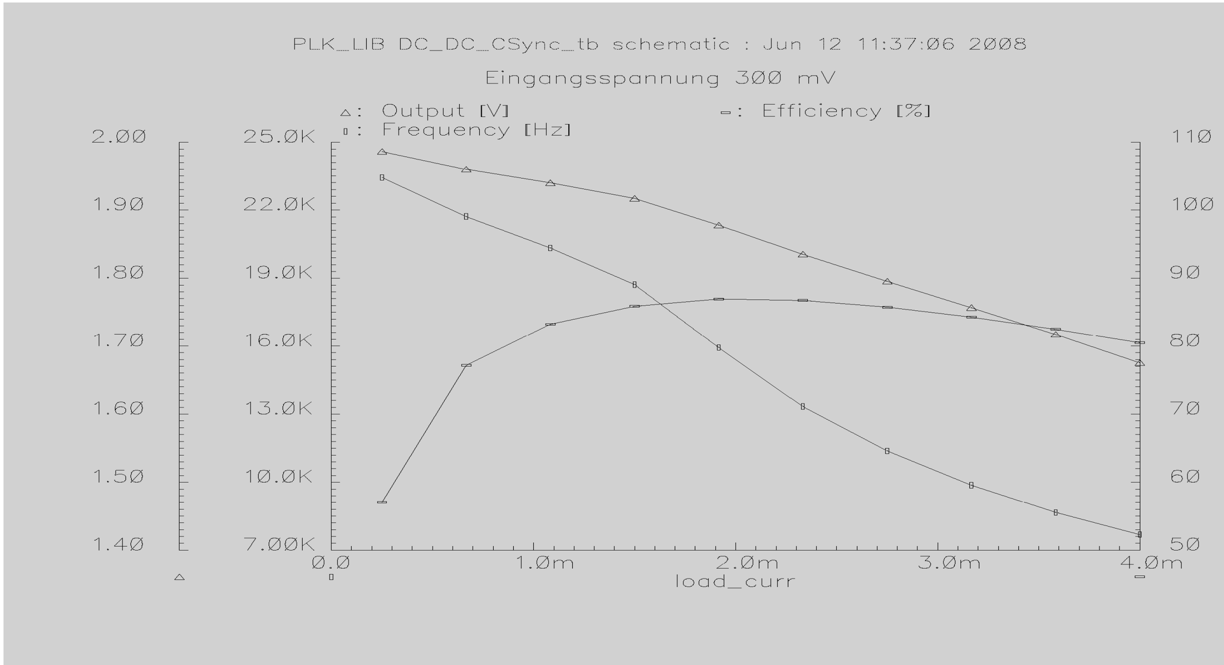
Low-voltage DC-DC Converter

- ASIC-Design: Layout (CMOS 180 nm, 1.5*1.5mm) and simulations (L1=500µH, L2=12mH)
- all components on chip except transformer and output C





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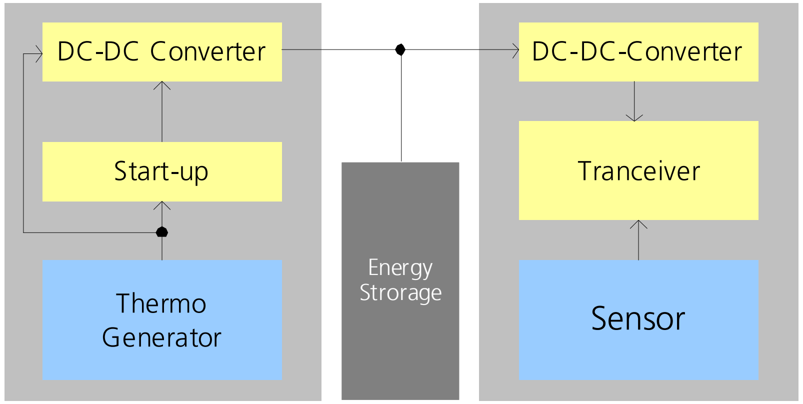
Low-voltage DC-DC Converter

- low-voltage dc-dc converter makes operation with low thermal gradient possible
- thermo-electrical power supply for wireless sensors
- T-sensor and transceiver supplied with 5 K delta T (2 mW)
- application example: human body



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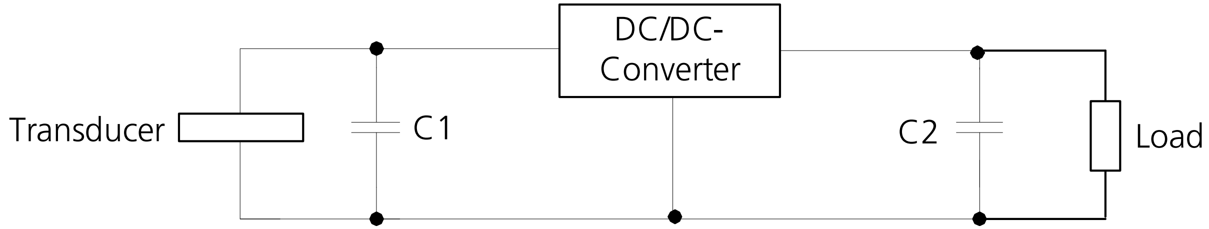
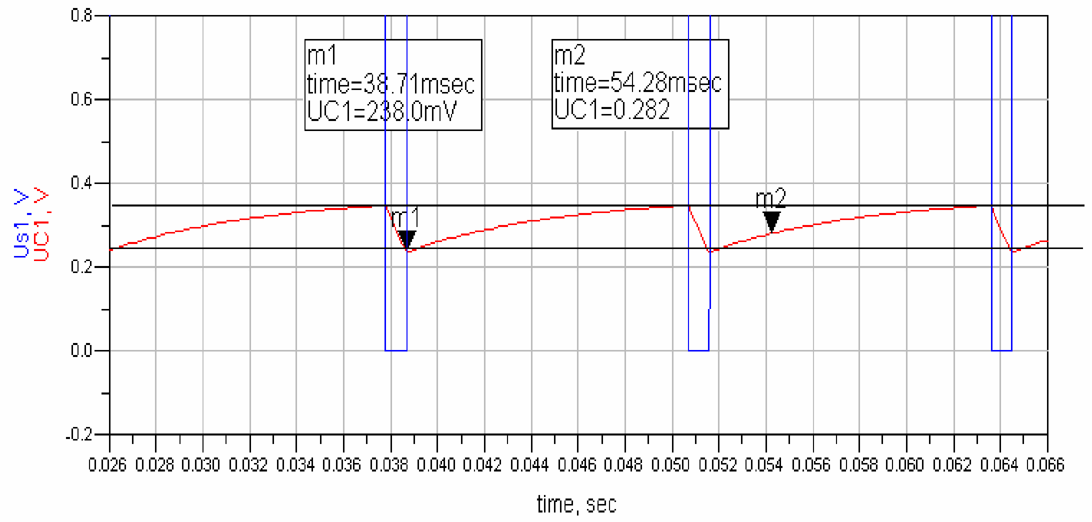
Discontinuous Mode

- supply / standby currents of dc-dc converters exceed output of transducers
- discontinuous mode converts energy in small time slots
- sleep mode reduces power consumption of converter
- working with higher currents improves efficiency of converter
- voltage detectors with small power consumption needed





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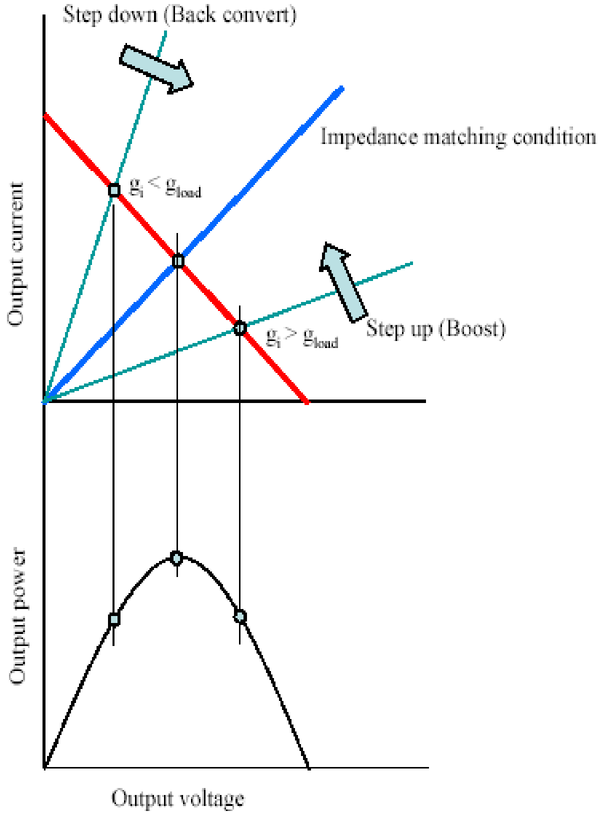
Maximum Power Point Tracker (MPP)



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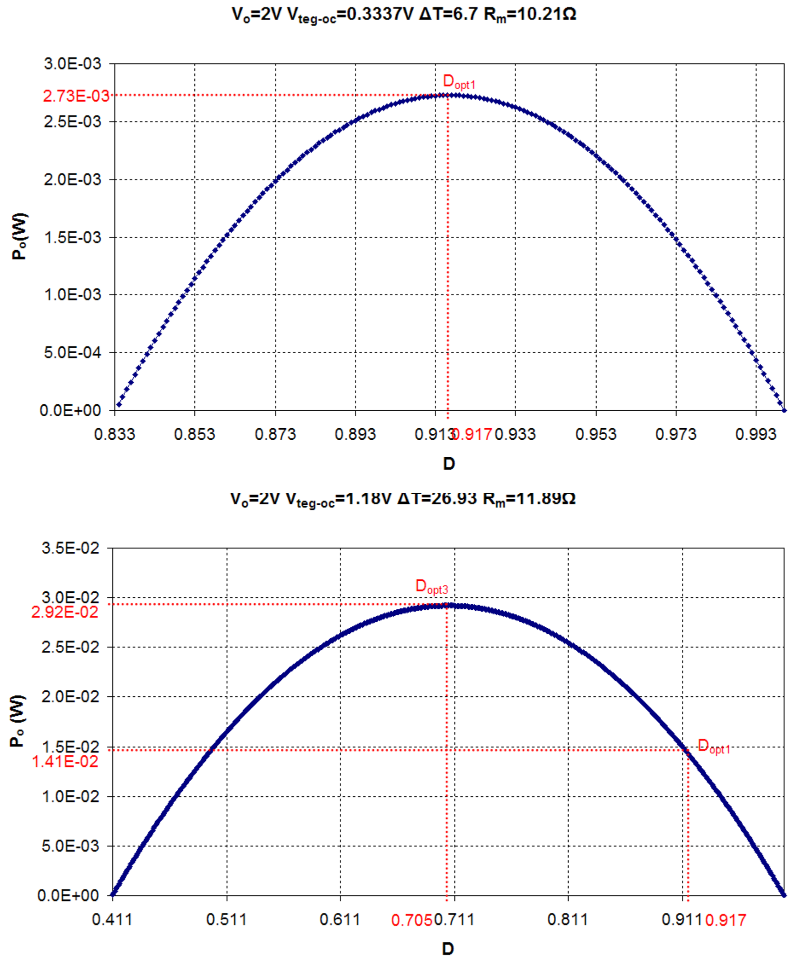
- changing environmental conditions influence efficiency of transducers
- intelligent power management ensures maximum power output
- impedance matching with regard on maximum output power (state-of-the-art: dc-dc with voltage regulation loop)
- energy storage required
- most concepts with µC and digital HW are not suited for Energy Harvesting due to power consumption
- analogue circuit techniques (opamp with 1µA) can solve conflict with lower precision

Maximum Power Point Tracker

- switching frequency (duty cycle) is controlled and output power measured
- increasing output power: duty cycle is changed further in the same direction and vice versa
- example: If the optimum duty cycle with ΔT=6.7K, Dopt1, is fixed, with ΔT=26.93K more than 100% of power is lost
- application: indoor-outdoor use



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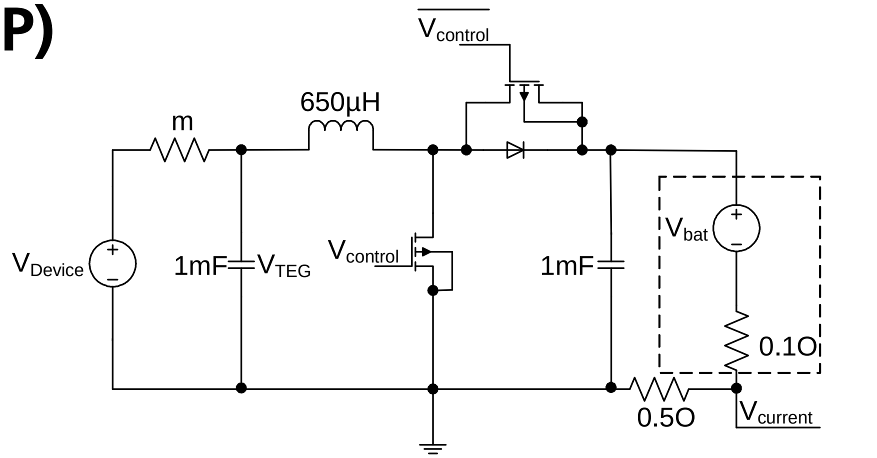
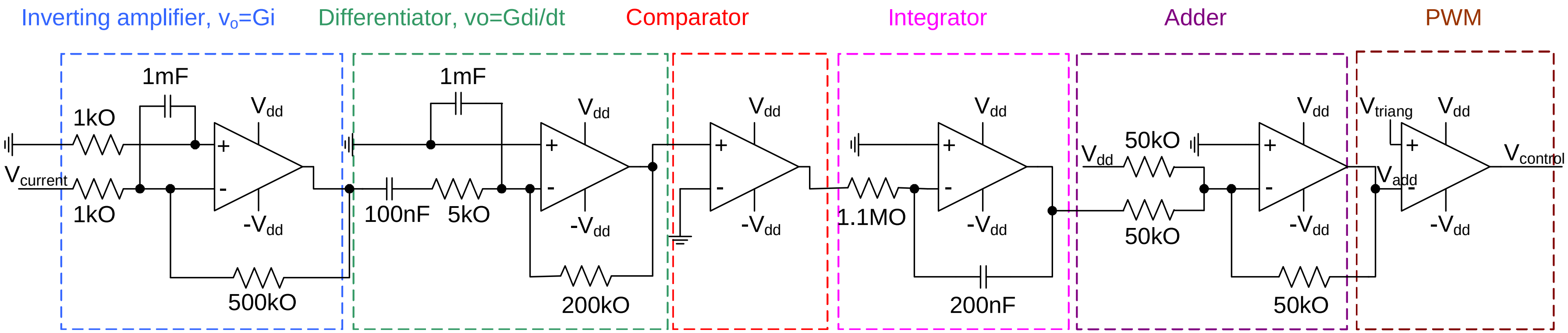
Maximum Power Point Tracker (MPP)

- battery voltage nearly constant, thus only current measurement
- implementation via feedback loop for control of switching transistor (Vcurrent >> Vcontrol)





Summary and Conclusion

- state-of-the art power management circuits not well suited for energy harvesting
- first improvements under development
- additional functionality required (detectors, start-up circuits, MPP trackers), which must not degrade efficiency
- IC technology development facilitates energy harvesting
- still a lot of unsolved challenges: leakage / standby currents, efficiency versus load range, start-up / supply voltage

Thank you for your attention! **…any questions?**

Energy Harvesting Transducers - Summary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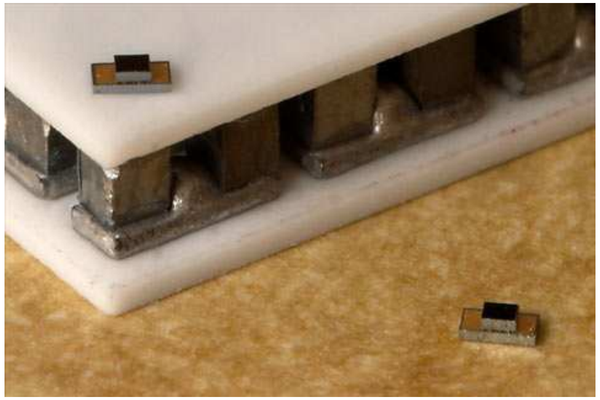

Fraunhofer IPM

Energy Source	Power Density for 10 Years
Solar (outdoor)	15,000 µW/cm³
Solar (indoor)	6 µW/cm³
Vibrations (piezoelectric)	250 µW/cm³
Vibrations (electrostatic)	50 µW/cm³
Acoustic noise	0.003 µW/cm³ (at 75 dB)
Temperature gradient (thermoelectric)	15 µW/cm³ (at 10 °C gradient)
Batteries (non-rechargeable)	45 µW/cm³ (for one year)
Batteries (rechargeable)	7 µW/cm³ (for one year)
Hydrocarbon fuel (micro heat engine)	333 µW/cm³ (for one year)
Fuel cells (methanol)	280 µW/cm³ (for one year)

(Shad Roundy, Paul K. Wright, Jan Rabaey, Computer Communications 26 (2003) 1131-1144)

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