Micro-Power Management for Energy Harvesting Power Sources and Storage Devices

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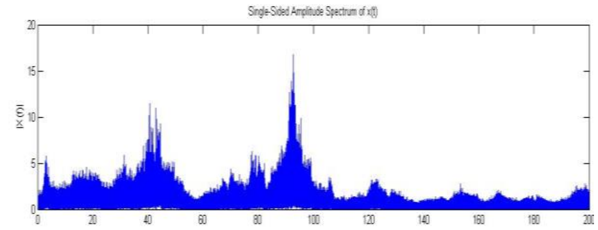
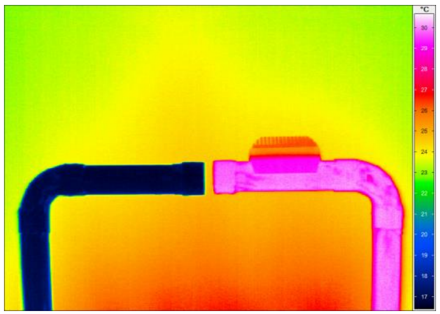
Micro-Power Management for Energy Harvesting Power Sources and Storage Devices

1. DC-DC converters
2. Ultra-low voltage start-up circuits
3. Bipolar inputs stages
4. MPPT implementations
5. Micro-battery management circuits
6. Application examples

Micro-Power Management
Introduction - Motivation

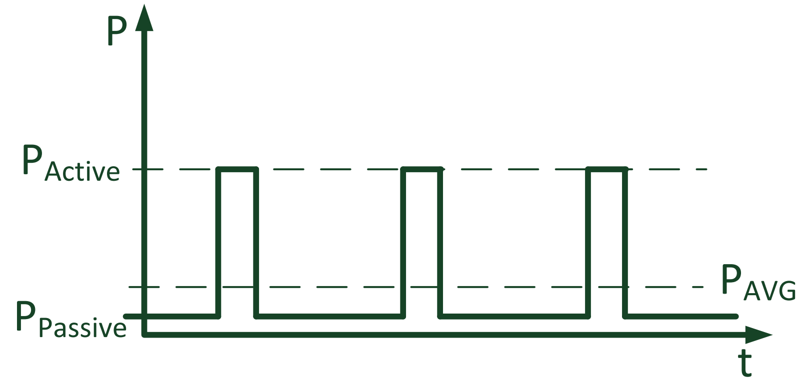
- Energy harvesting uses ambient energy sources
- Ambient sources are intermittent, unstable, often not predictable
- Transducers have a given current (I) and voltage (V) profile, depending on design (size, area, material, architecture, etc.)
- Storage devices have given charge voltages and currents
- Application circuits have a given power requirement (function, technology, supply voltage etc.)
- **Power management to adapt harvester to energy storage and application device**

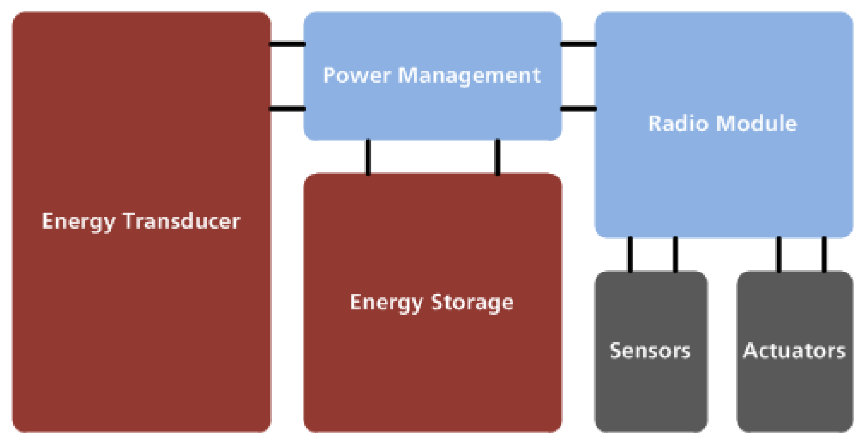




Micro-Power Management
Introduction - Motivation

- Energy transducer
- Power management
- Energy storage





Micro-Power Management
Introduction - Motivation

Energy Source	Challenge	Typical Impedance	Typical Voltage	Typical Power Output	Cost
Light	Conform to small surface area; wide input voltage range	Varies with light input Low kΩ to 10s of kΩ	DC: 0.5V to 5V [Depends on number of cells in array]	10μW-15mW (Outdoors: 0.15mW-15mW) (Indoors: <500μW)	**$0.50 to $10.00**
Thermal	Small thermal gradients; efficient heat sinking	Constant impedance 1Ω to 100s of Ω	DC: 10s of mV to 10V	0.5mW-10mW (10° C gradient)	**$1.00 to $30.00**
Vibrational	Variability of vibrational frequency	Constant impedance 10s of kΩ to 100kΩ	AC: 10s of volts	1μW-20mW	**$2.50 to $50.00**
RF & Inductive	Coupling & rectification	Constant impedance Low kΩs	AC: Varies with distance and power 0.5V to 5V	Wide range	**$0.50 to $25.00**

Steve Grady, Cymbet Corporation, „Advanced Energy Harvesting Power Chain Design Techniques", IDTechEX Energy Harvesting and Storage, Santa Clara, USA, November 2013.

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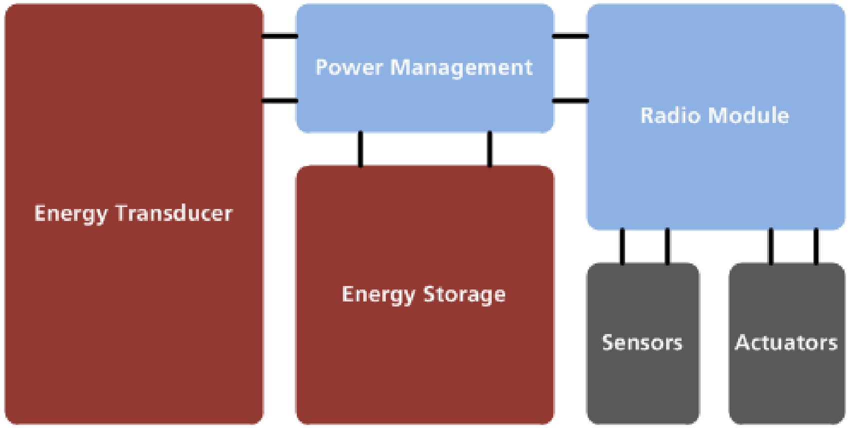
Micro-Power Management
Introduction - Motivation

- To use minimum amount of energy, power management has to cope with smallest voltages or currents
- To use the maximum available energy, the power management needs a large voltage input range
- Since power from harvester is very low, power management (DC-DC, MPPT, etc.) may not consume significant quiescent currents: High efficiency, especially at low currents



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Micro-Power Management
Agenda

1. **DC-DC converters**
2. Ultra-low voltage start-up circuits
3. Bipolar inputs stages
4. MPPT implementations
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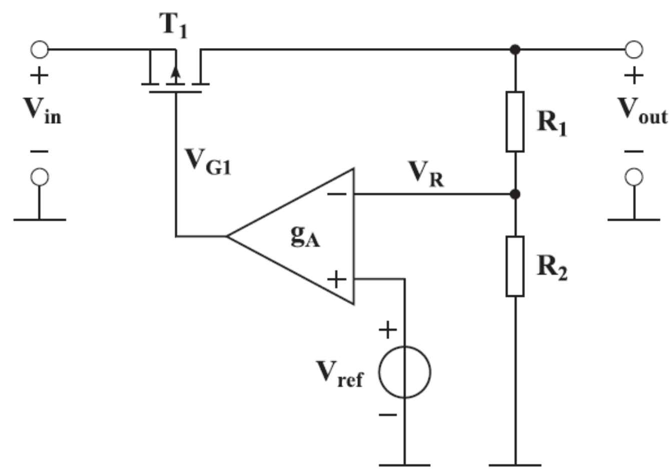
Micro-Power Management
DC-DC Converters

Linear Regulator

- Feedback of a control deviation to a control element / transistor T1
- Transistor works in linear mode: regulated ohmic resistor
- No large devices (L,C)
- $V_{in} > V_{out}$
- Power consumption depending on voltage difference (e.g. 3.7 > 1.8, 1 mA = 19 mW)
- R_1 and R_2 to reduce quiescent current
- Large control transistor > small resistor > Low-Dropout (LDO) regulator



$$V_{out} = V_{ref}\left(1 + \frac{R_2}{R_1}\right)$$

$$P \approx I_{out} \cdot (V_{in} - V_{out})$$

[spies, mateu, pollak 2015]

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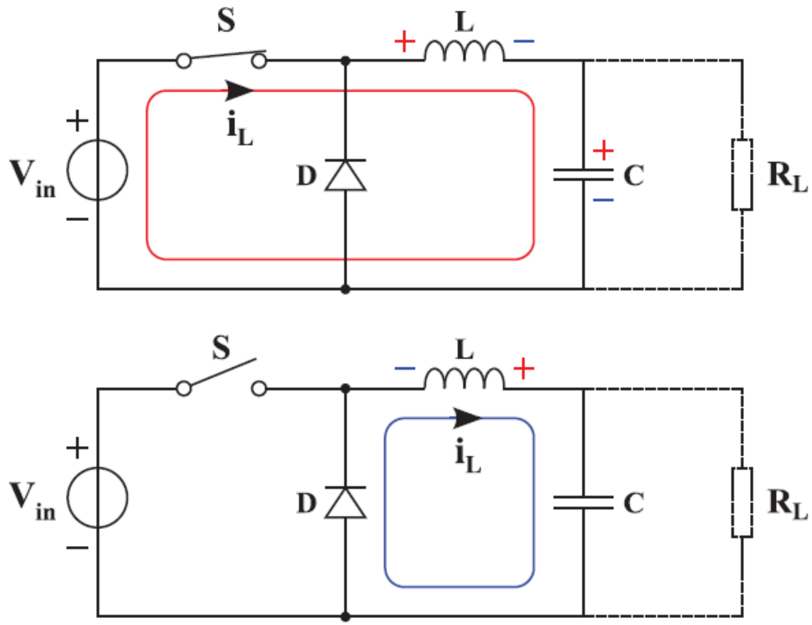
Micro-Power Management
DC-DC Converters

Switching regulator: Buck

- Transistor works like a switch (on: high current, no voltage drop; off: no current, high voltage drop)
- Good efficiency, independent on voltage difference
- Mainly ohmic losses in inductor and switching losses
- Output noise no problem for batteries
- Depending on combination of devices also up-converting (Boost)



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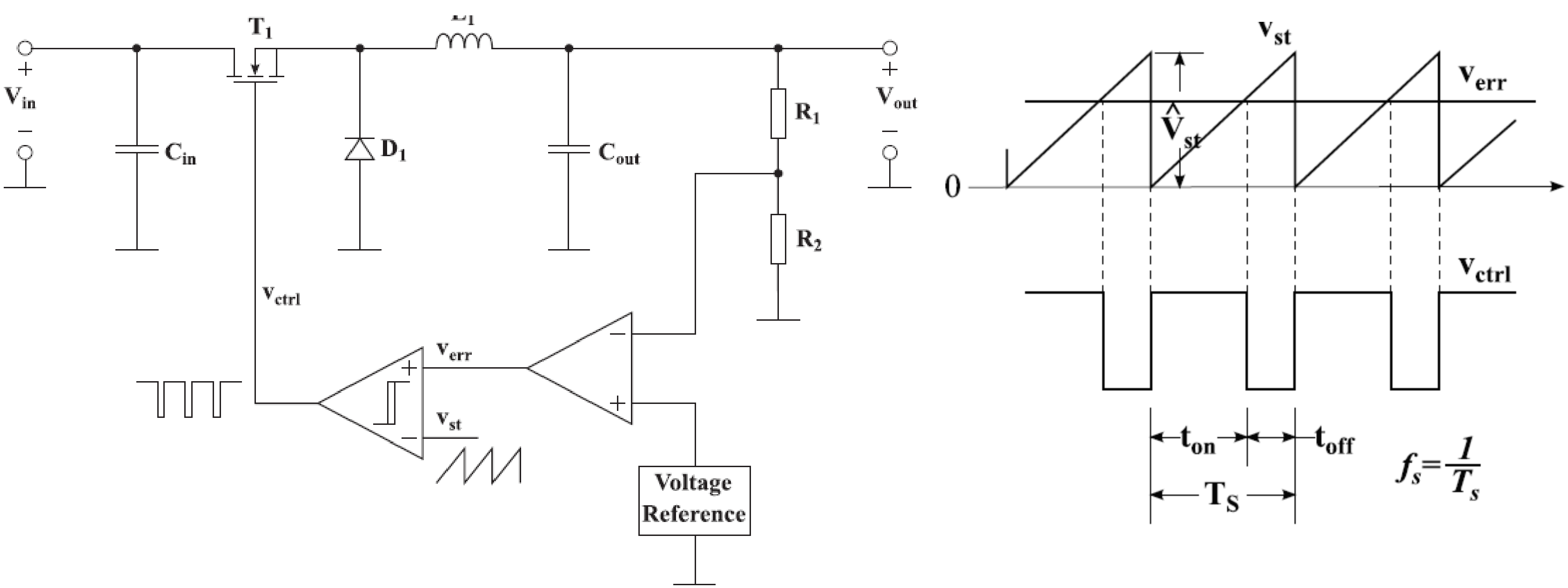
Micro-Power Management
DC-DC Converters

Switching regulator: Buck

- Operation



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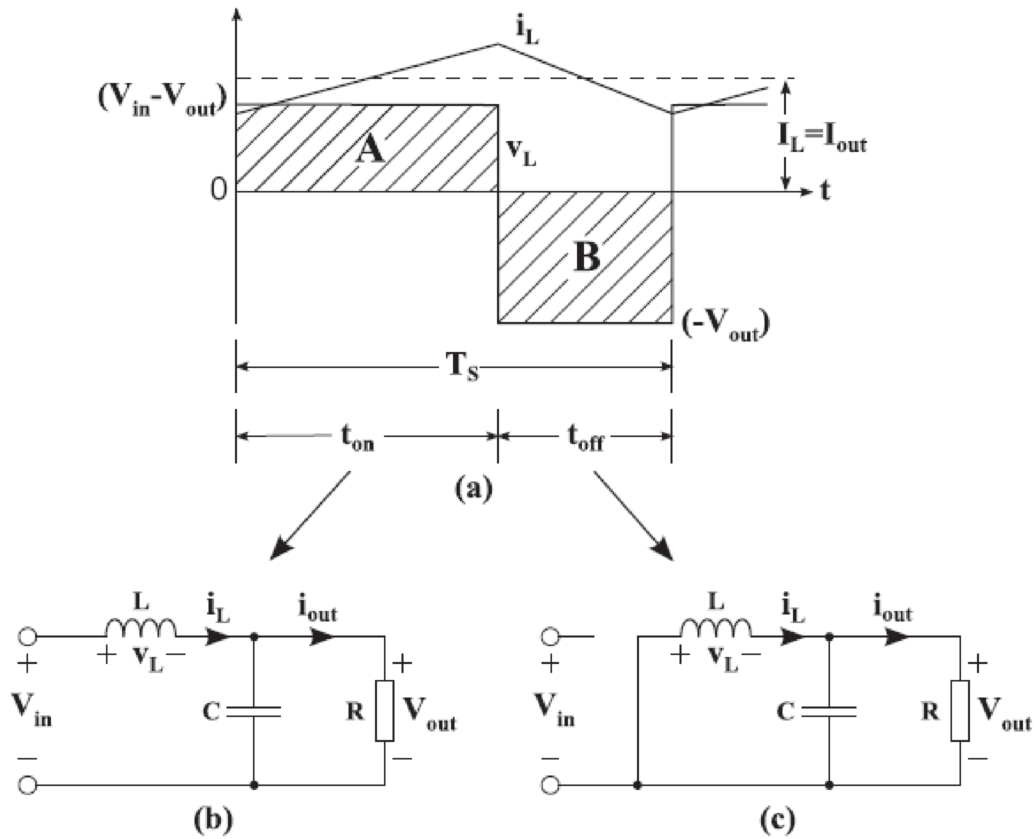
Micro-Power Management
DC-DC Converters

Switching regulator: Buck

- Operation

$$D = \frac{t_{on}}{T_s}$$

$$\frac{I_{out}}{I_{in}} = \frac{V_{in}}{V_{out}} = \frac{1}{D}.$$



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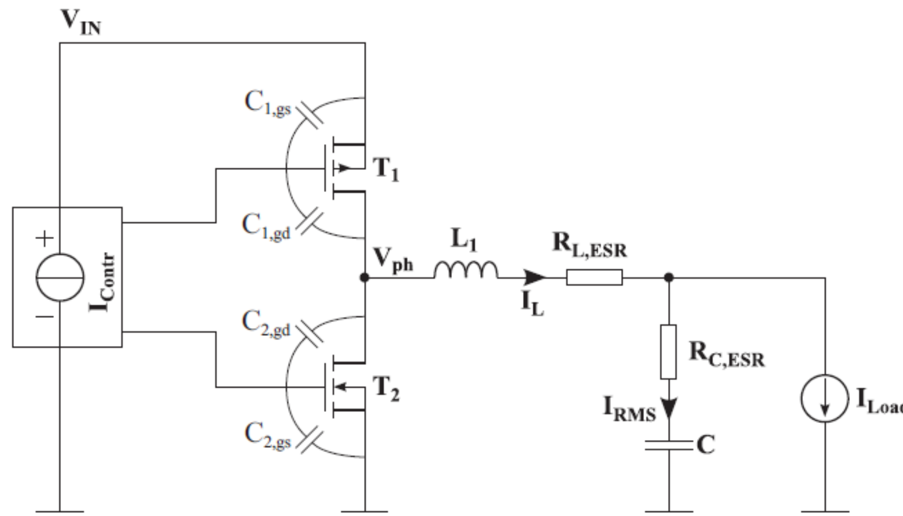
Micro-Power Management
DC-DC Converters

Switching regulator: Buck

- Synchronous step-down converter with parasitic elements
- Diode replaced by Transistor
- R_{ESR}: Equivalent Series Resistance of Ls and Cs
- $R_{T1/2}$: On-Resistance of T1 and T2
- Qg: Gate charge of transistors
- I_{contr}: Consumption of control electronics (diff- amp, reference, oscillator, etc.)
- P_{SW}: Switching loss due to voltage and current overlap



$$P_{\mathrm{l,Load}} = (R_{\mathrm{L,ESR}} + R_{T1/2}) \cdot I_{\mathrm{Load}}^2$$

$$P_{\mathrm{l,RMS}} = (R_{\mathrm{L,ESR}} + R_{\mathrm{C,ESR}} + R_{T1/2}) \cdot I_{\mathrm{RMS}}^2.$$

$$P_{\mathrm{Contr}} \approx I_{\mathrm{Contr}} \cdot V_{\mathrm{in}} + (Q_{\mathrm{g,T1}} + Q_{\mathrm{g,T2}}) \cdot V_{\mathrm{in}} \cdot f_{\mathrm{s}}$$

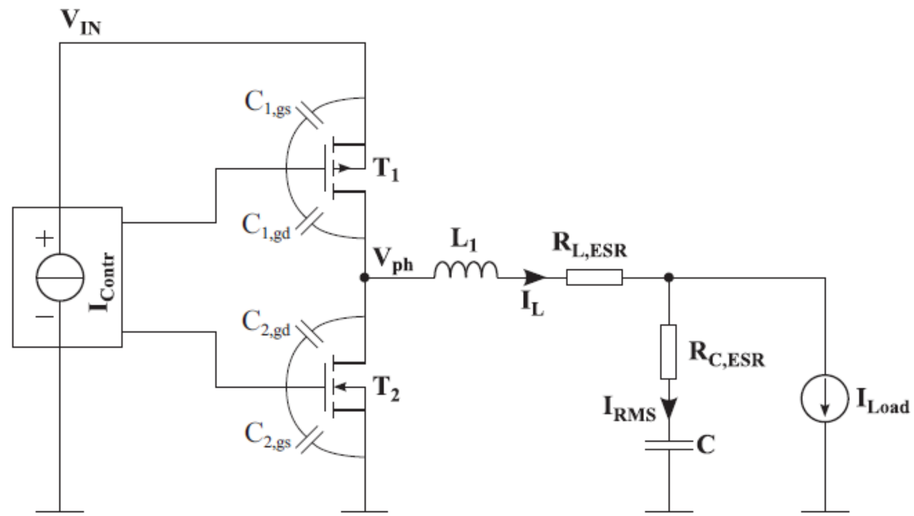
$$P_{\mathrm{SW}} \approx V_{\mathrm{in}} \cdot I_{\mathrm{Load}} \cdot t_{\mathrm{sum}} \cdot f_{\mathrm{s}},$$

[spies, mateu, pollak 2015]

Micro-Power Management
DC-DC Converters

Switching regulator: Buck

- Light loads: P_{contr} is dominant
- High loads: P_l and P_{SW} is dominant
- Optimization
  - Trade-off between size and efficiency
  - L is biggest part
  - Big L has low ESR and leads to low switching frequency



$$P_{\mathrm{l,Load}} = (R_{\mathrm{L,ESR}} + R_{T\,1/2}) \cdot I_{\mathrm{Load}}^2$$

$$P_{\mathrm{l,RMS}} = (R_{\mathrm{L,ESR}} + R_{\mathrm{C,ESR}} + R_{T\,1/2}) \cdot I_{\mathrm{RMS}}^2.$$

$$P_{\mathrm{Contr}} \approx I_{\mathrm{Contr}} \cdot V_{\mathrm{in}} + (Q_{\mathrm{g,T1}} + Q_{\mathrm{g,T2}}) \cdot V_{\mathrm{in}} \cdot f_{\mathrm{s}}$$

$$P_{\mathrm{SW}} \approx V_{\mathrm{in}} \cdot I_{\mathrm{Load}} \cdot t_{\mathrm{sum}} \cdot f_{\mathrm{s}},$$

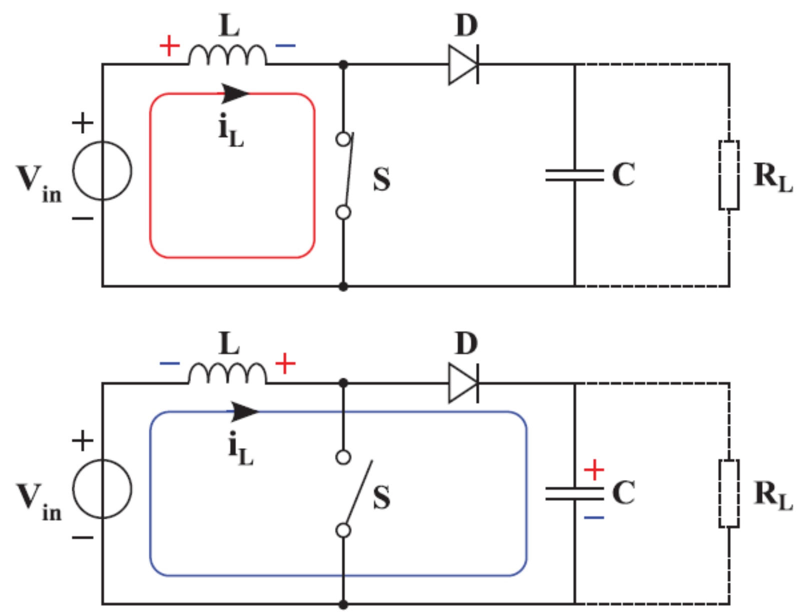
[spies, mateu, pollak 2015]

Micro-Power Management
DC-DC Converters

Switching regulator: Boost

- Step-up voltages from lower sources

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{T_s}{t_{\text{off}}} = \frac{1}{1 - D}$$



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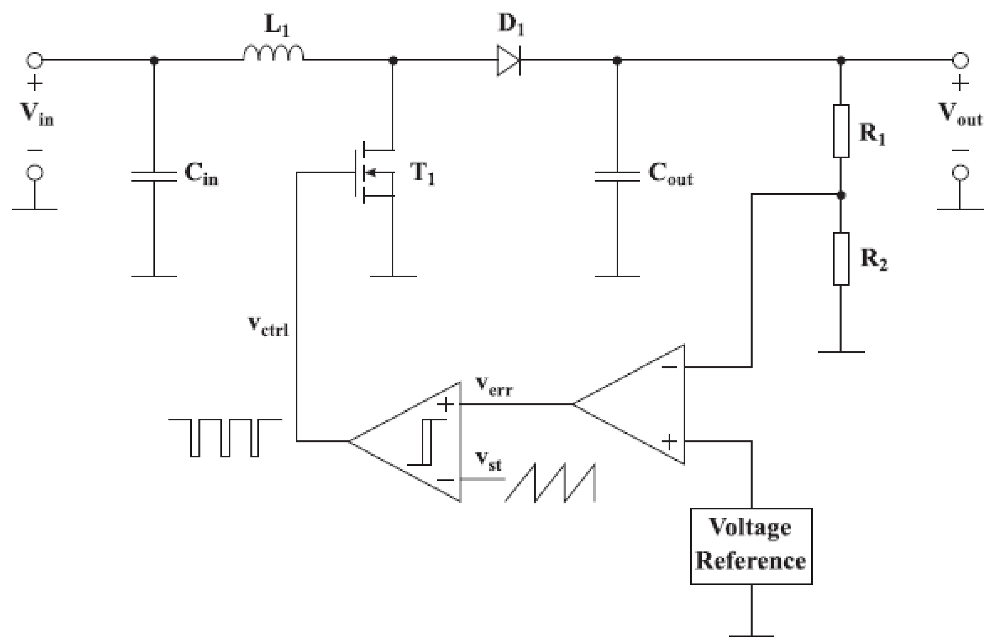
Micro-Power Management
DC-DC Converters

Switching regulator: Boost

- Step-up voltages from lower sources



$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{T_s}{t_{\text{off}}} = \frac{1}{1-D}$$

[spies, mateu, pollak 2015]

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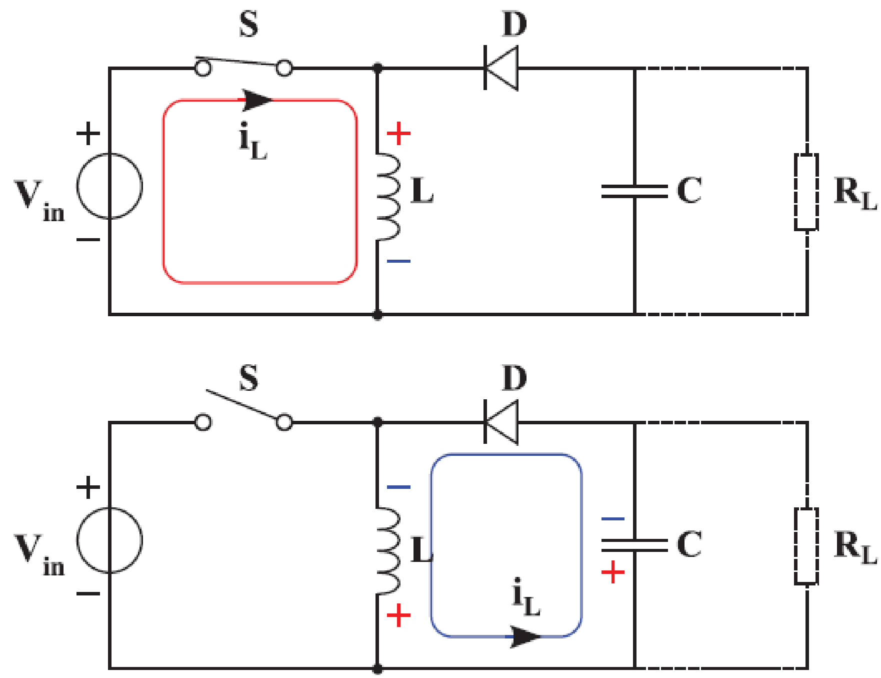
Micro-Power Management
DC-DC Converters

Switching regulator: Buck-Boost

- Step-up or step-down of voltages

$$\frac{V_{out}}{V_{in}} = \frac{D}{1 - D}$$



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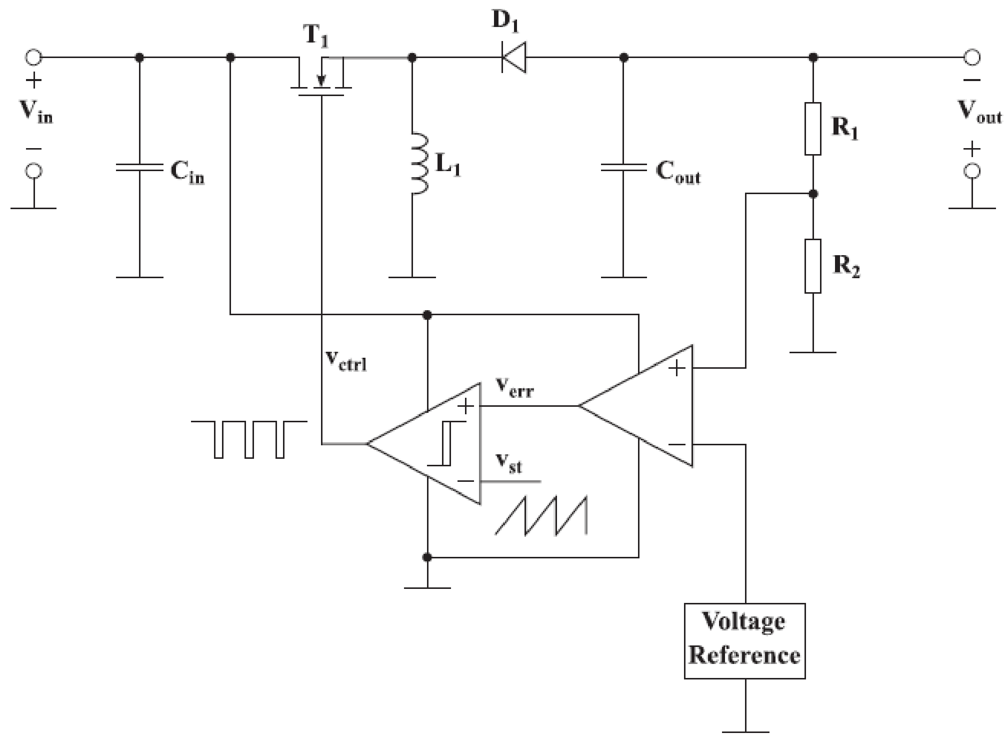
Micro-Power Management
DC-DC Converters

Switching regulator: Buck-Boost

- Step-up or step-down of voltages



$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{D}{1 - D}$$

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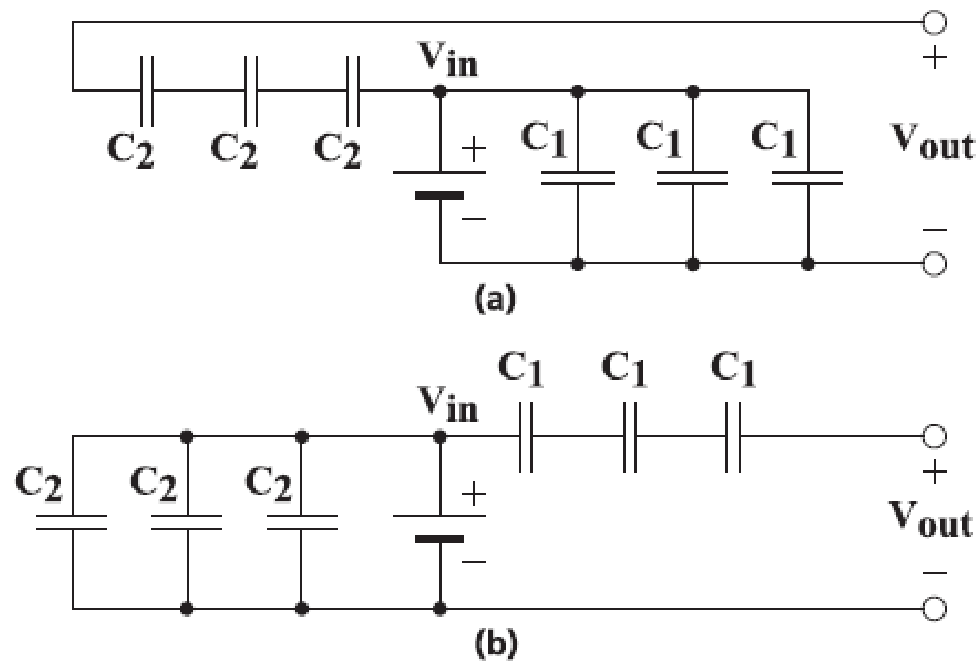
Micro-Power Management
DC-DC Converters

Switching regulator: Charge pump

- Capacitors used for voltage adaption
- No inductors needed
- Capacitors can be integrated on a chip easier than inductors



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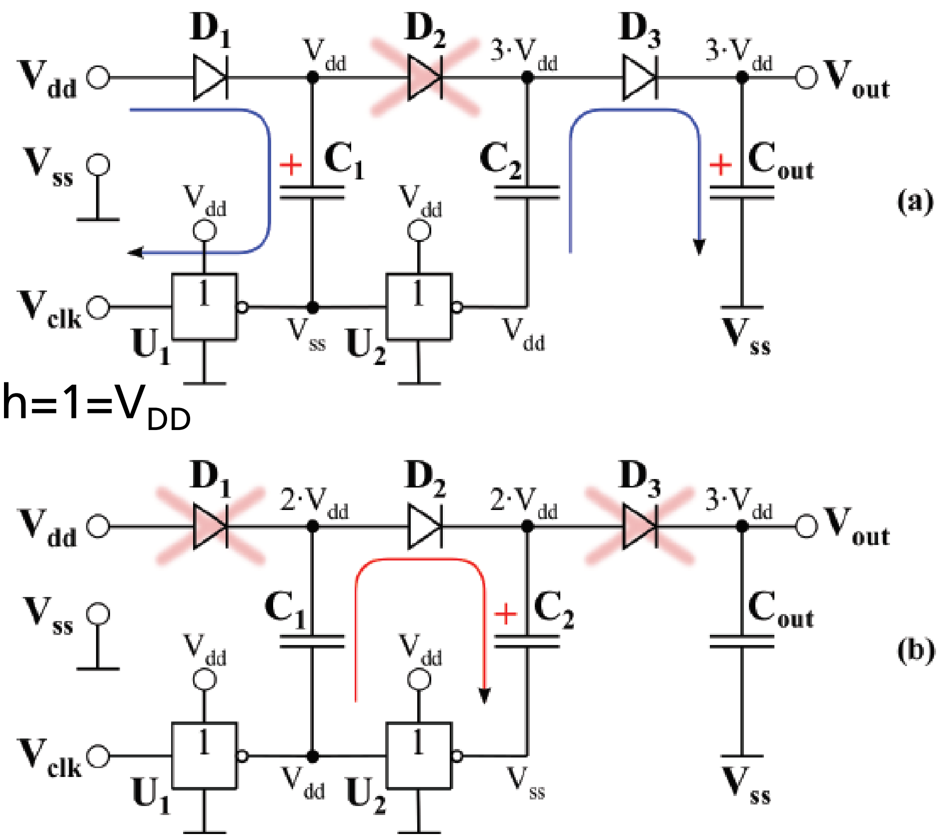
Micro-Power Management
DC-DC Converters

Switching regulator:
Charge pump

- Dickenson charge pump
- Diodes have a forward-voltage drop
- Use of switched transistors instead



High=1=V_{DD}

Low=0=V_{SS}

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Micro-Power Management
DC-DC Converters

Overview

Converter Type	Vin – Vout	Remark
Linear	Vin > Vout	small currents, small voltage drop, no large passives (L,C), no output noise
Buck	Vin > Vout	high efficiency
Boost	Vin < Vout	high efficiency
Buck-Boost	Vin >,< Vout	high efficiency
Charge Pump	Vin >,< Vout	high integration level, no Ls, small currents

Micro-Power Management
Agenda

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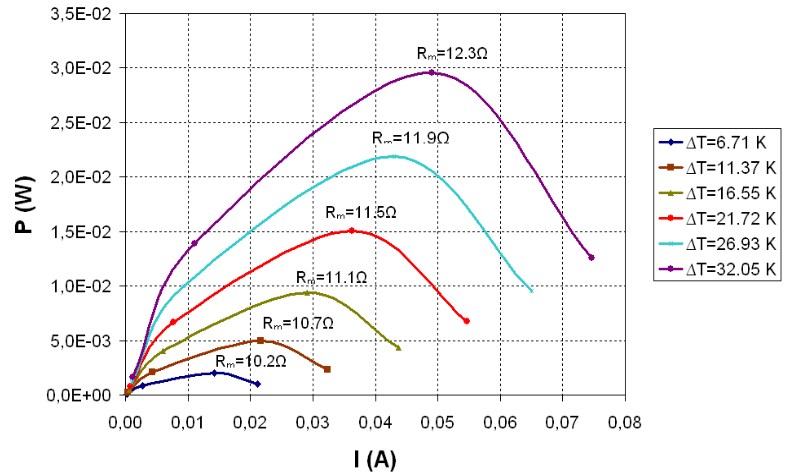
Micro-Power Management
Ultra Low Voltage Start-up Circuits

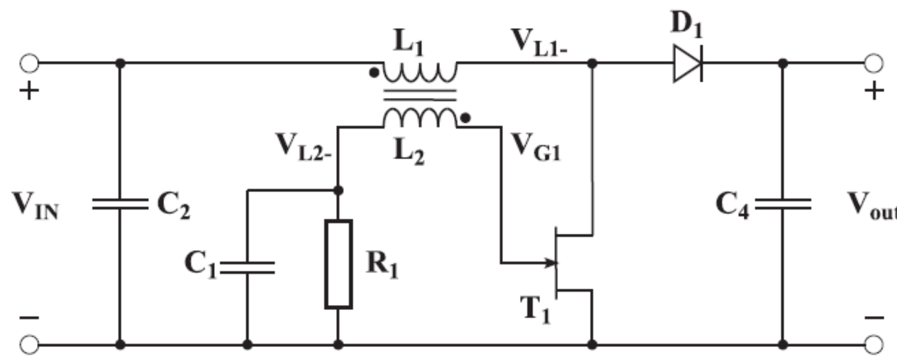
- TEGs and solar cells as well as electro-dynamic (inductive) generators provide only very small voltages
- To use minimum amounts of ambient energy, ultra low start-up voltage are required
- E.g. TEGs with 1 K provides 50 mV



Micro-Power Management
Ultra Low Voltage Start-up Circuits

Meissner oscillator based converter

- Self-oscillating structure with feedback-loop
- Simple regulation loop because no clock circuit is needed
- JFET – Junction FET: Normally-on transistor, with negative threshold voltage
- Works like a boost converter, but control is done by coupled inductor
- No power transfer from L1 to L2 (compare to flyback converter): L2 has not to be optimized for low ESR



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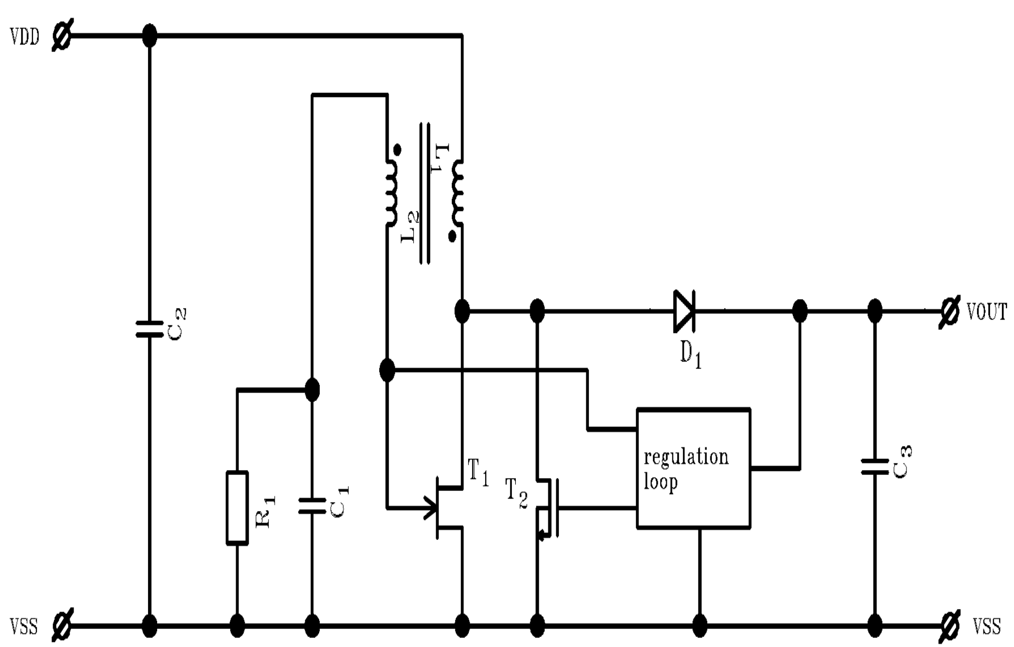
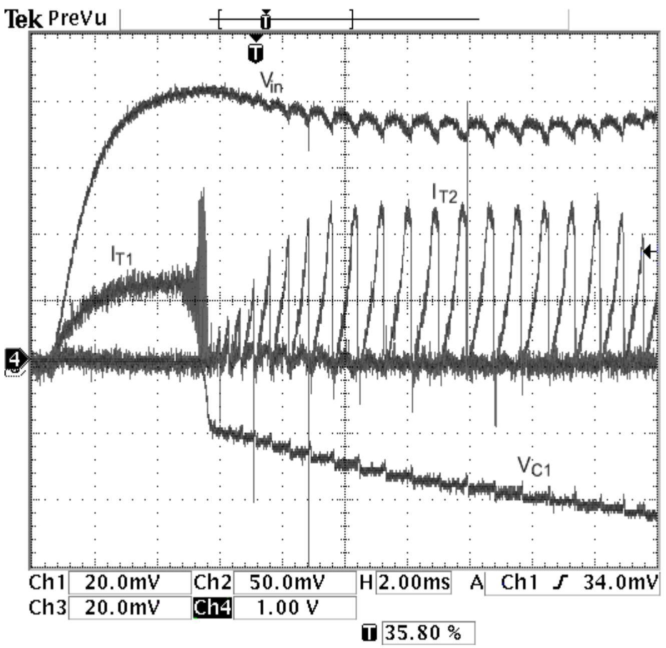
Micro-Power Management
Ultra Low Voltage Start-up Circuits

- Practical Implementation: DC-DC converter starts with 20 mV due to JFET (Junction Field Effect Transistor) and transformer
- MOS Transistor with low ESR in parallel to JFET to reduce losses after start-up

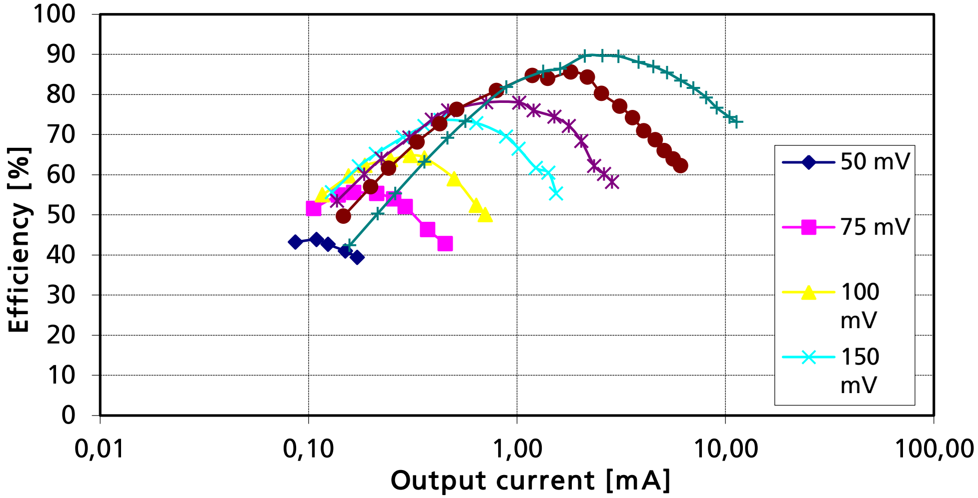




[spies, mateu, pollak 2015]

Micro-Power Management
Ultra Low Voltage Start-up Circuits

- Start-up with 20 mV
- Use of state-of-the-art thermoelectric generators at lowest thermal gradients
- e.g 1 K at human body, windows, pipes, etc.



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Micro-Power Management
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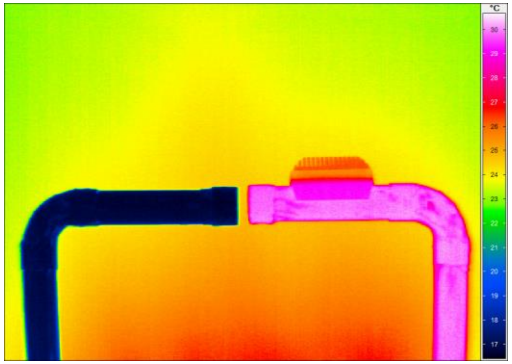
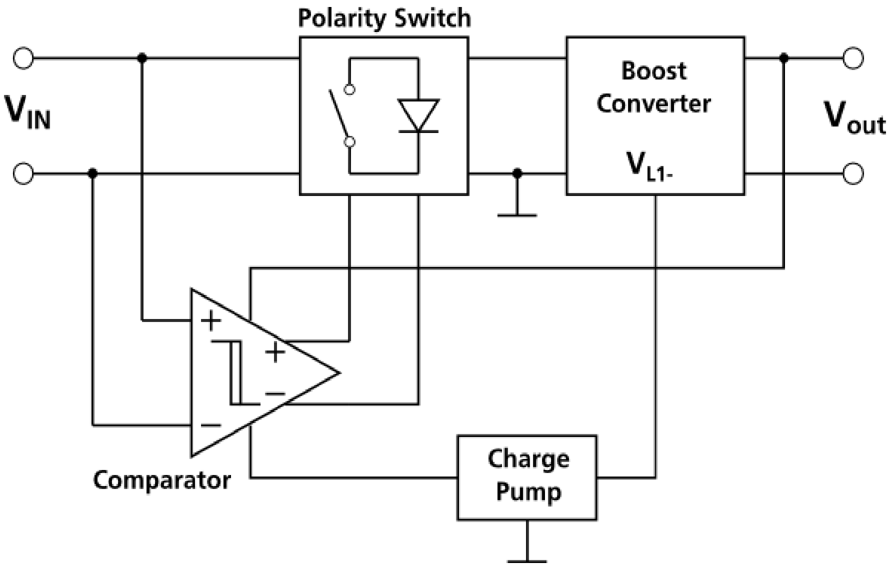
Micro-Power Management
Bipolar Input Stages

- Output polarity is dependent on the direction of the temperature gradient
- Capability to work with positive and negative input voltages
- Applications: Windows, heaters, water pipes, air condition air, etc.
- Straight-forward: bridge rectifier, but voltage drop
- Polarity switch
- Controlled by a comparator, with dual voltage supply





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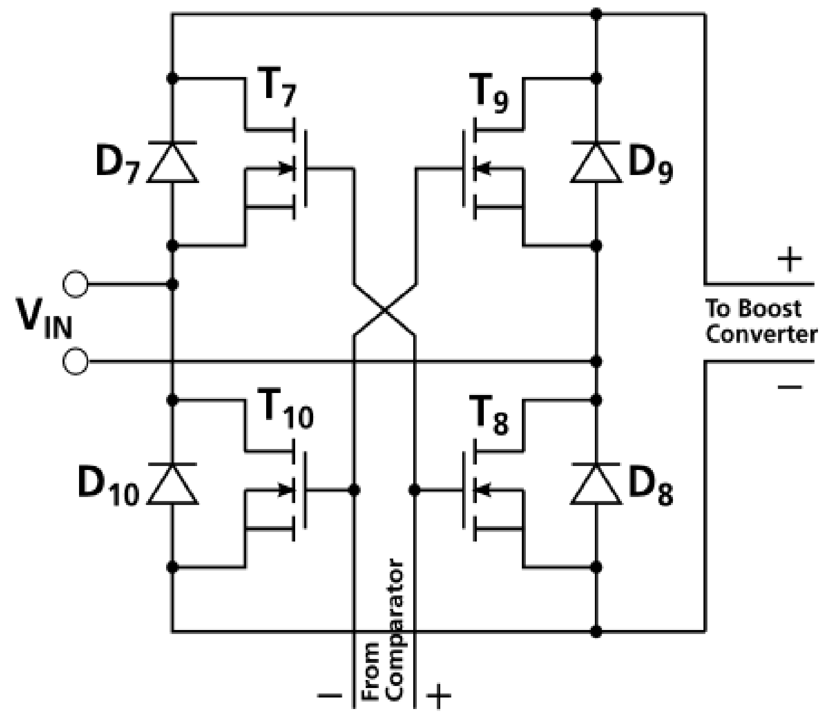
Micro-Power Management
Bipolar Input Stages

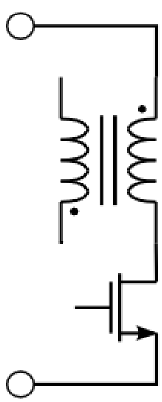
Polarity switch

- Diodes can be short-circuited by switches to prevent losing efficiency from the forward voltage drop
- Diodes are only active during start-up where still no supply voltage for the comparator is present
- Prototype: Start-up 150 mV, drop 40 mV, later on 5 mV

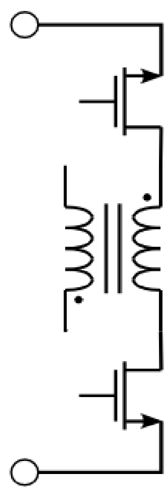


Micro-Power Management
Bipolar Input Stages

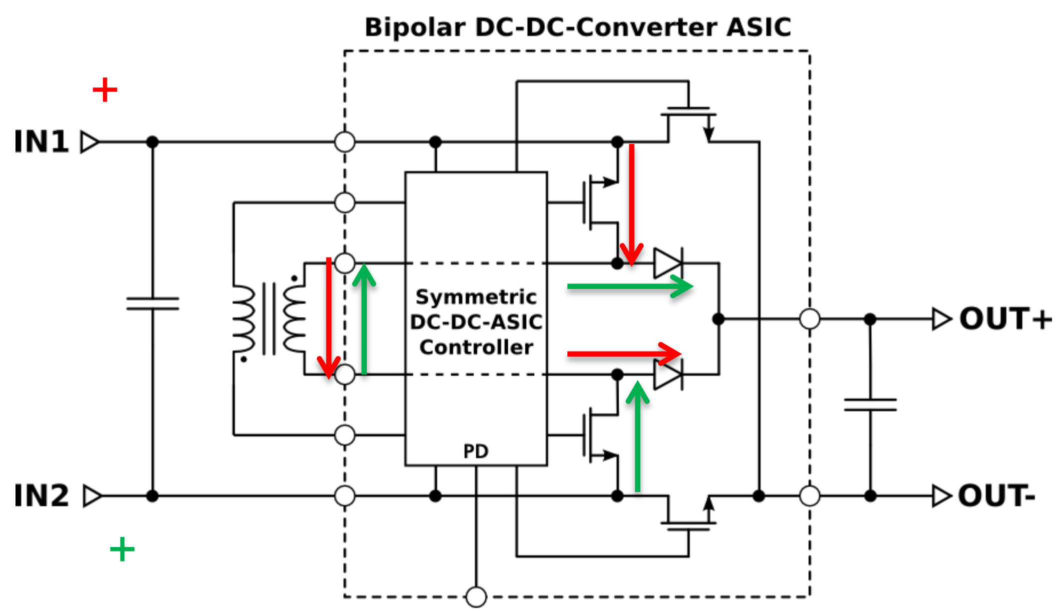
- Symmetric input stage: beneficial regarding start-up voltage, current and efficiency



Unipolar



Symmetric



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Micro-Power Management
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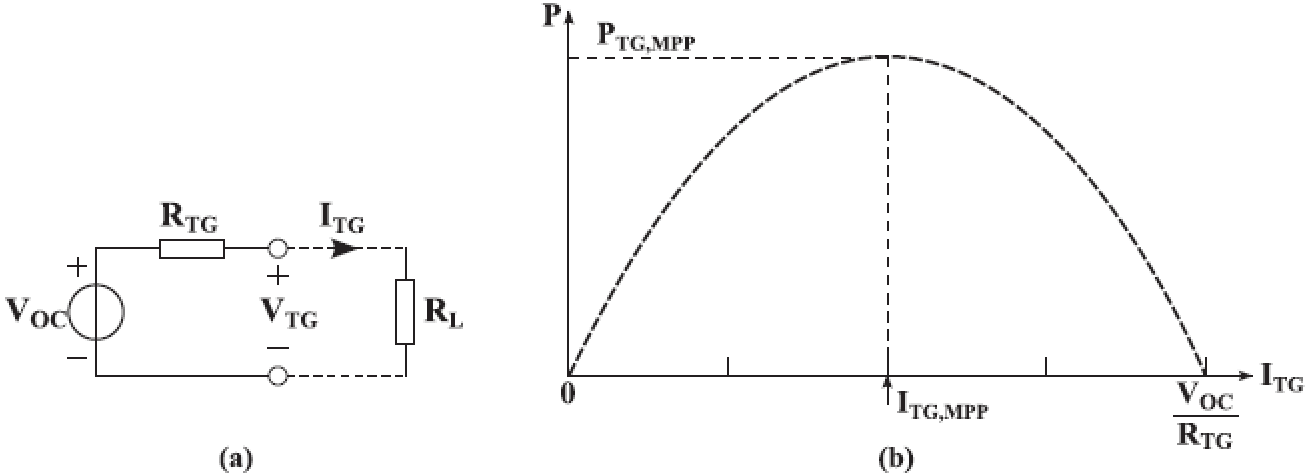
Micro-Power Management
MPPT Implementations



$$P_{TG} = (V_{OC} - R_{TG} I_{TG}) I_{TG} = V_{OC} I_{TG} - R_{TG} I_{TG}^2,$$

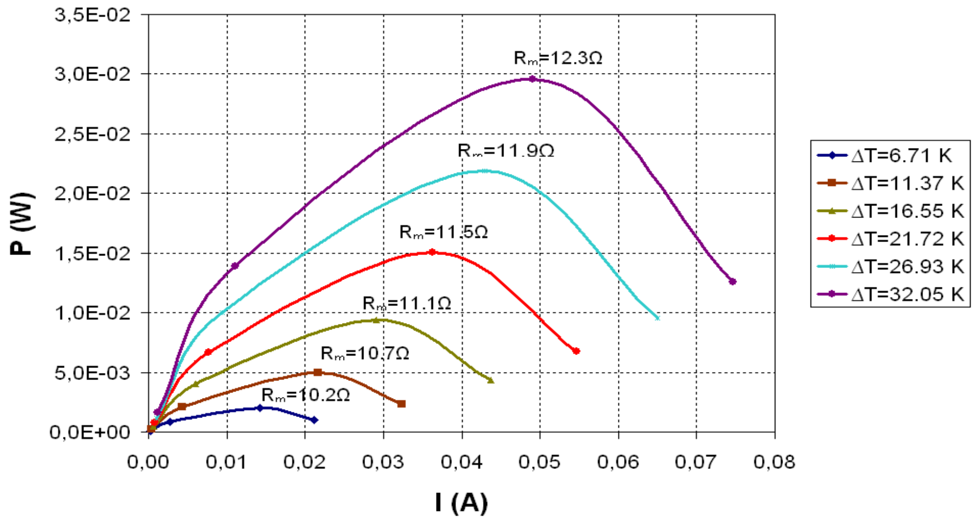
- Matching at MPP, when:

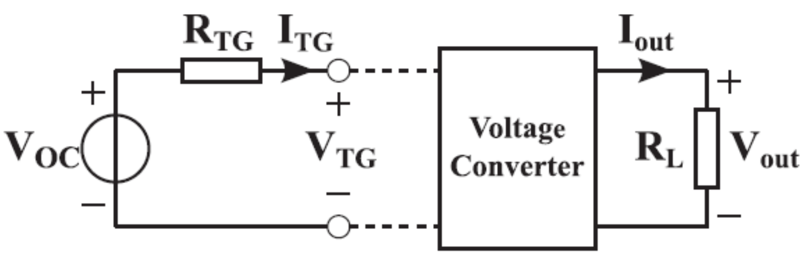
$$R_L = R_{TG} \text{ and } V_{TG} = \frac{V_{OC}}{2}$$

[spies, mateu, pollak 2015]

Micro-Power Management
MPPT Implementations

- Thermoelectric generators have a MPP
- MPP is a function of temperature
- With dynamic thermal conditions, power matching has to be adapted: MPPT





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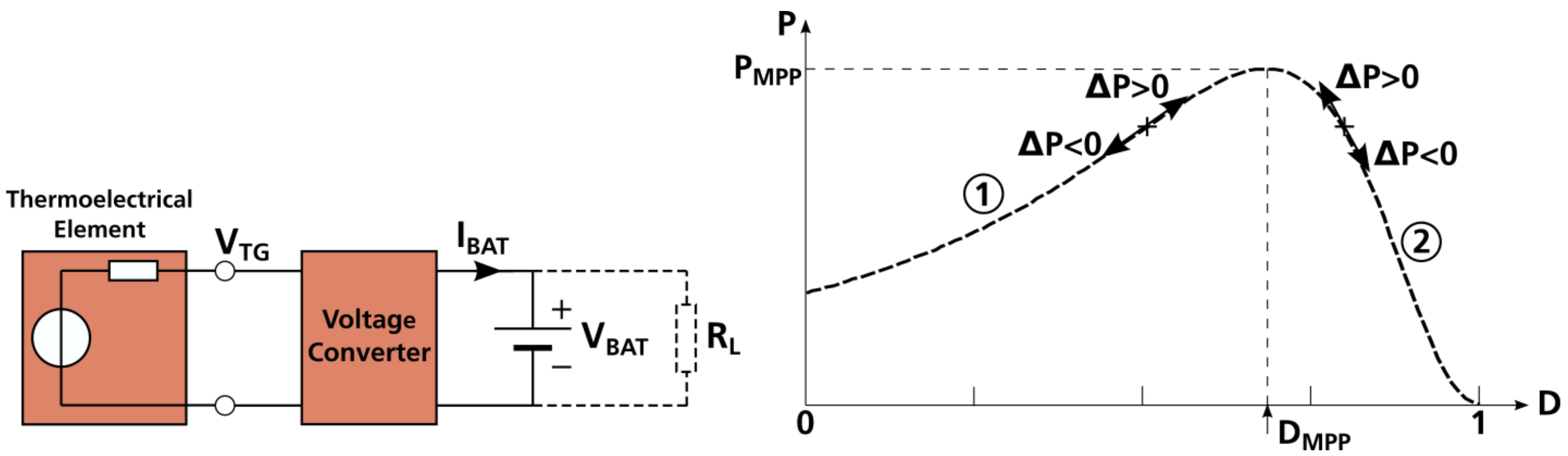
Micro-Power Management
MPPT Implementations

"Perturb-and-Observe" Algorithm

- Duty cycle of dc-dc converter is changed in a certain direction
- If current I_{BAT} (as a measure of the power) increases, direction of change is kept



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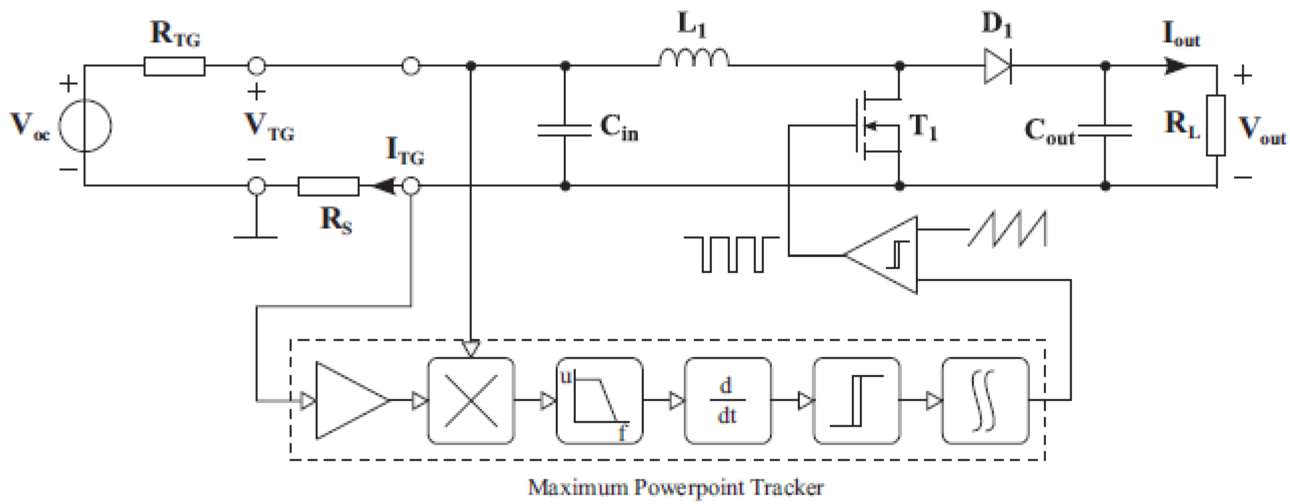
Micro-Power Management
MPPT Implementations

- Measuring power at input of voltage converter
- Filtering, differentiation, signature detection, integration: control duty cycle



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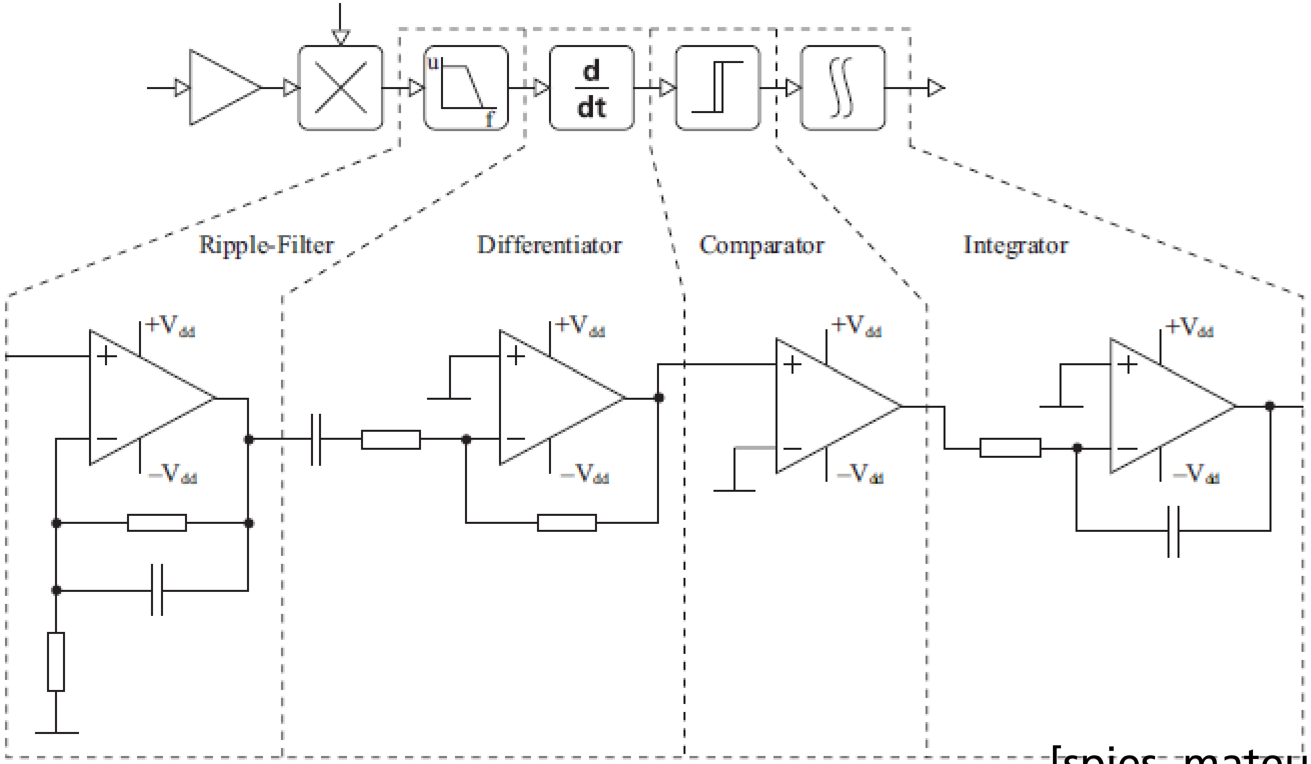
Micro-Power Management
MPPT Implementations

- Analog implementation: No µP, no ADC



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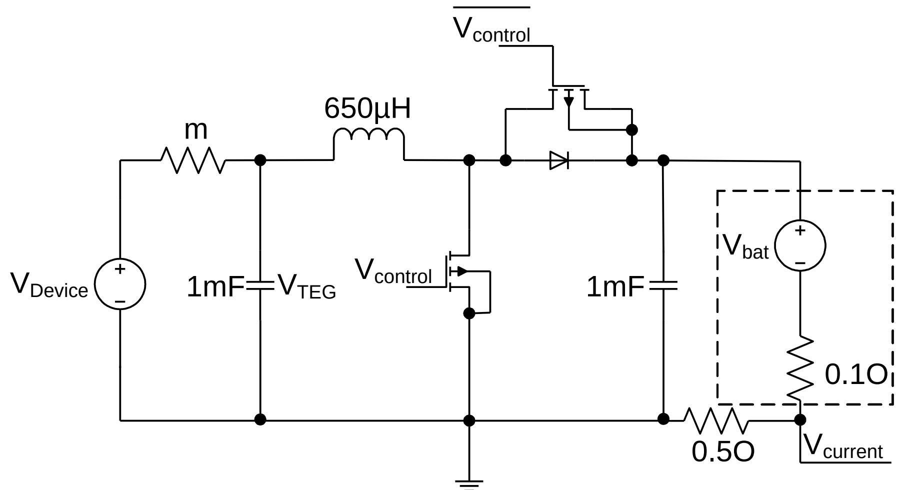
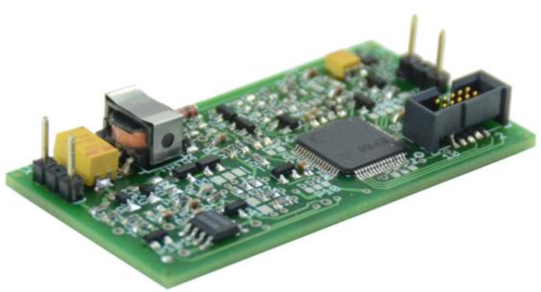
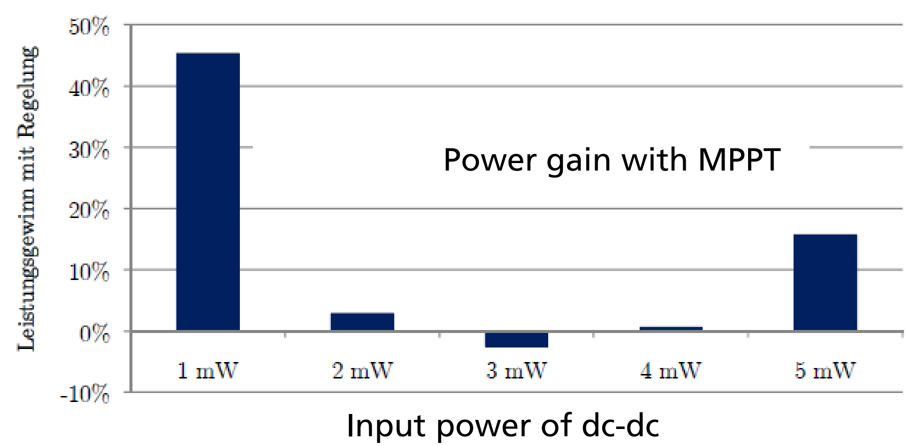
Micro-Power Management
MPPT Implementations

- Considering battery voltage as constant
- Measuring only current at the output
- Digital implementation with µP (often available from application)







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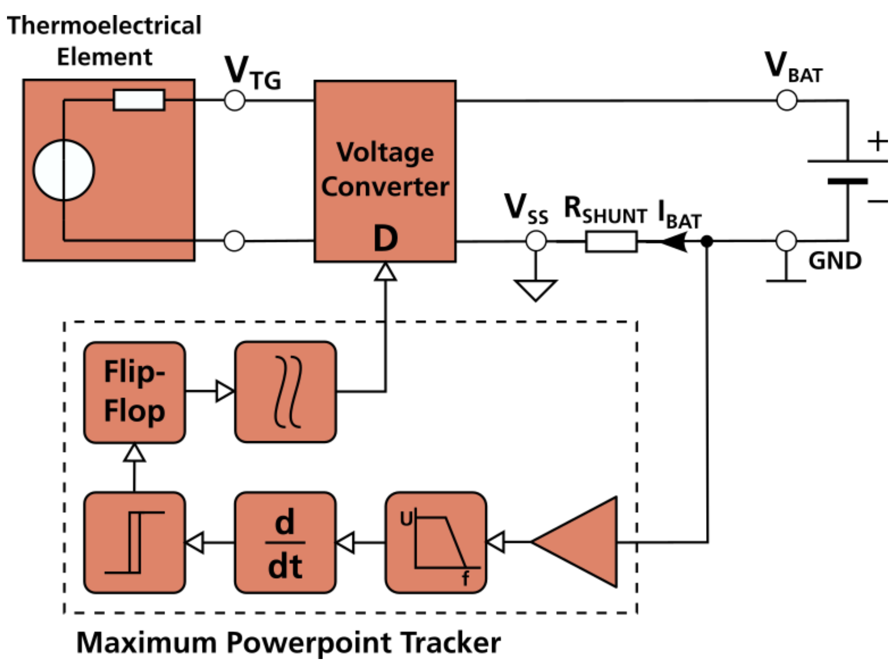
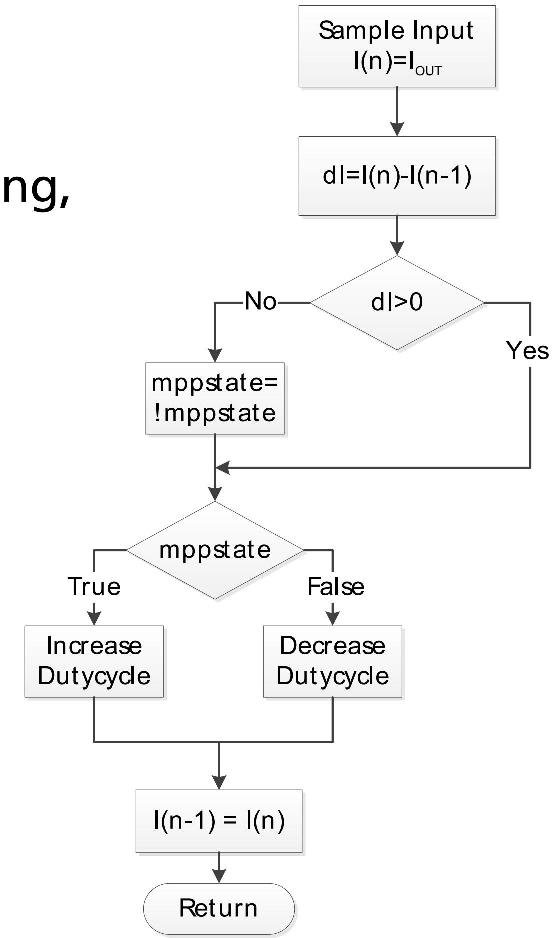
Micro-Power Management
MPPT Implementations

"Perturb-and-Observe" Algorithm

- Electrical implementation: amplification, filtering, differentiation, signature determination





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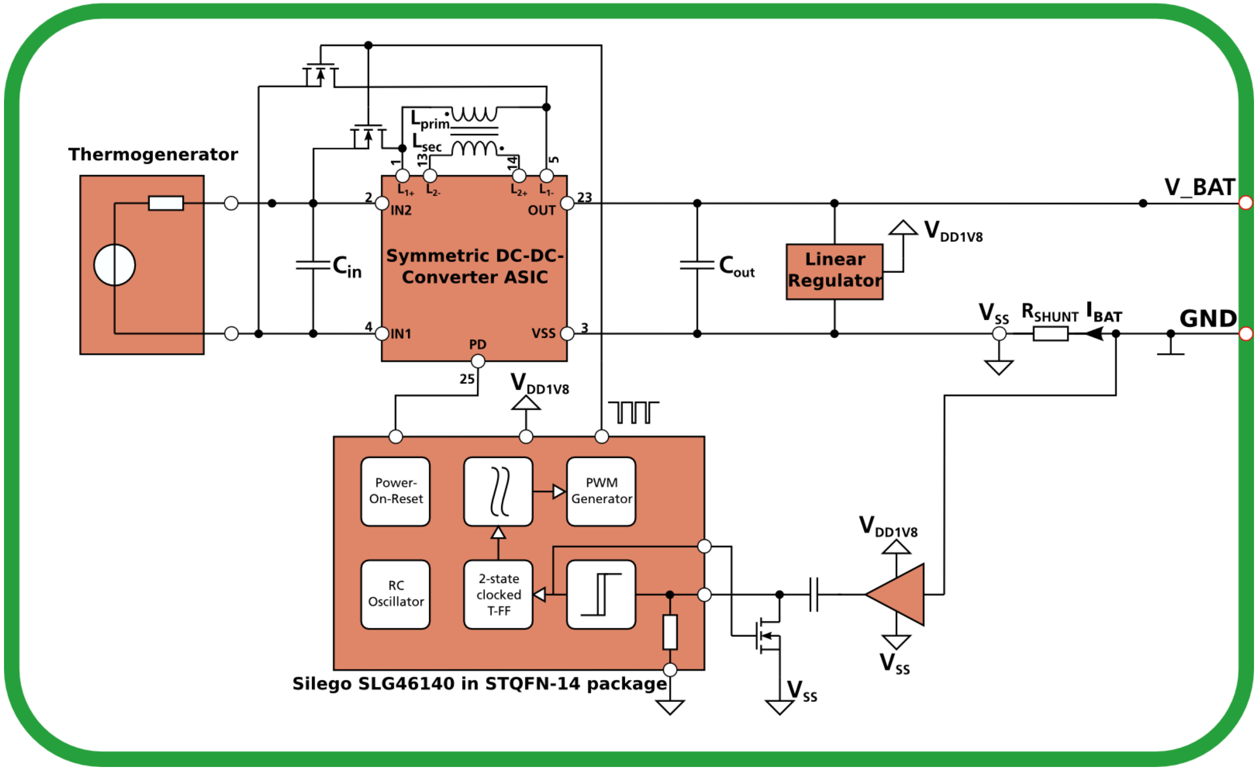
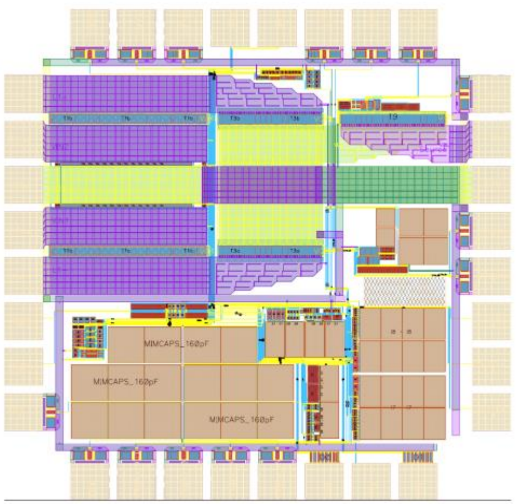
Micro-Power Management
MPPT Implementations

- Transformer 1:3
- Zero-threshold MOS, JFET or Depletion Mode
- MPPT: programmable Mixed-Signal IC Silego
- Consumption: 80 µA@1,8V



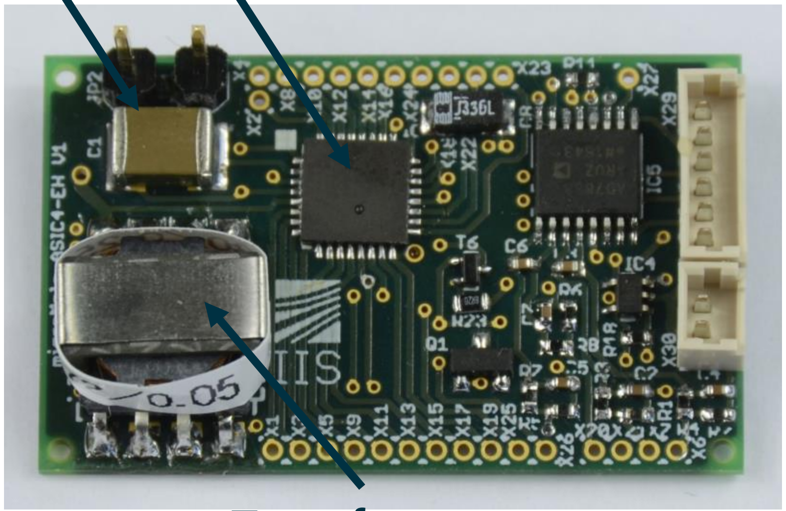
Micro-Power Management
MPPT Implementations

ASIC-Layout (1.2*1.2 mm)



Output capacitor

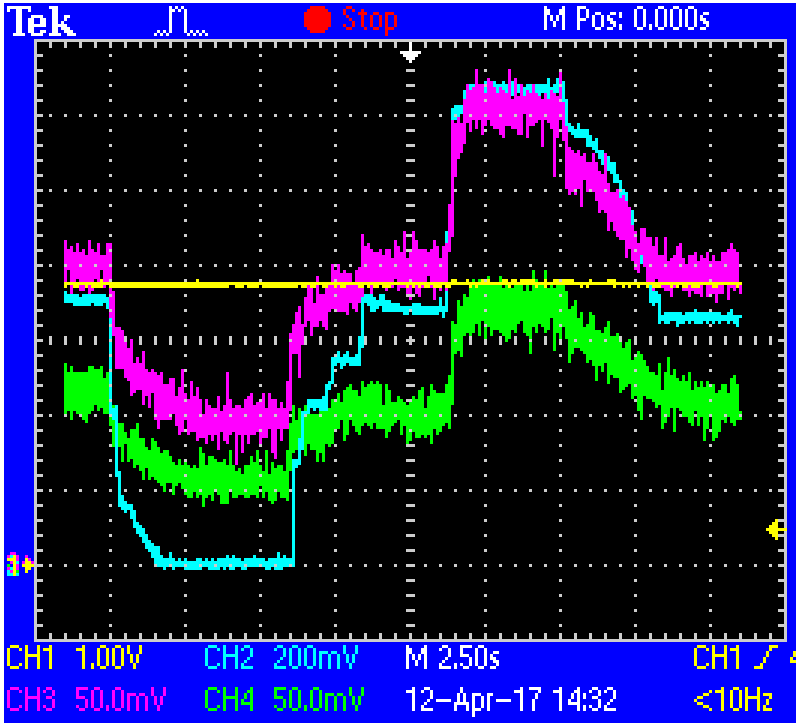
DC-DC IC

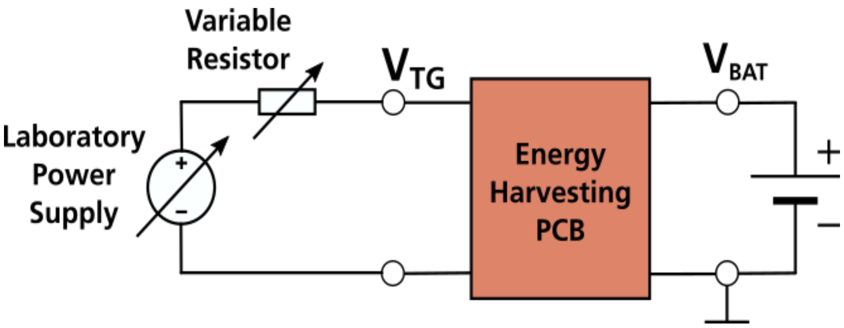


Transformer

Micro-Power Management
MPPT Implementations

- Power transfer matching (MPP): 0.5 of open circuit voltage provided to the load



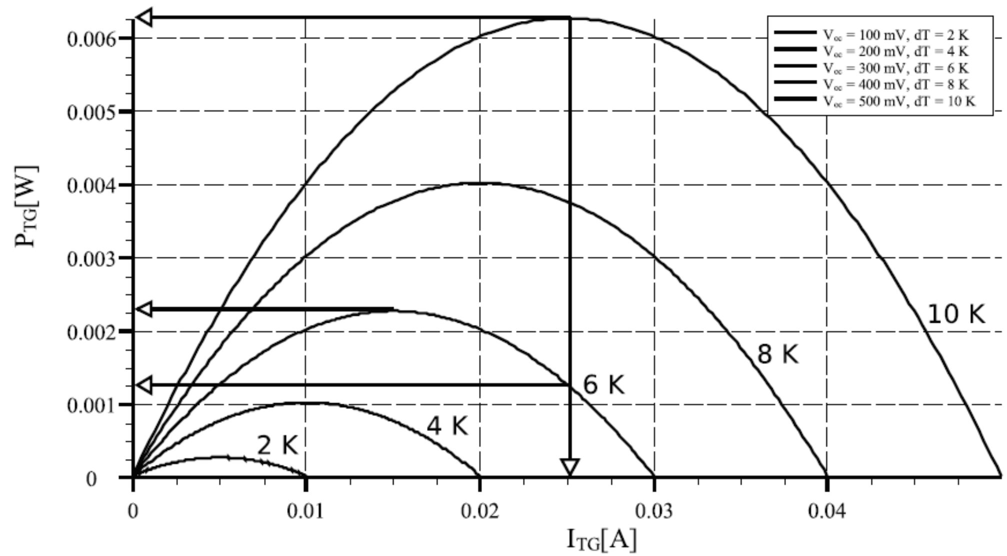


- CH1: V_{BAT}, battery voltage
- CH2: output current into battery
- CH3: voltage source at input, simulates open circuit voltage of TEG
- CH4: V_{TG}, simulates voltage of TEG

Micro-Power Management
MPPT Implementations

Example

- Change from 10K (6.2 mW, 25 mA) to 6K
- Keep operation point of 25 mA: 1.2 mW
- Adapt operation point to 15 mA: 2.5 mW
- Power gain 108 %



[spies, mateu, pollak 2015]

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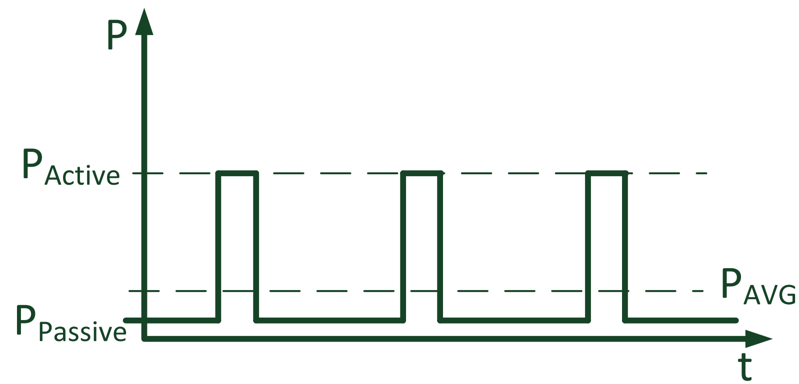
Micro-Power Management
Agenda

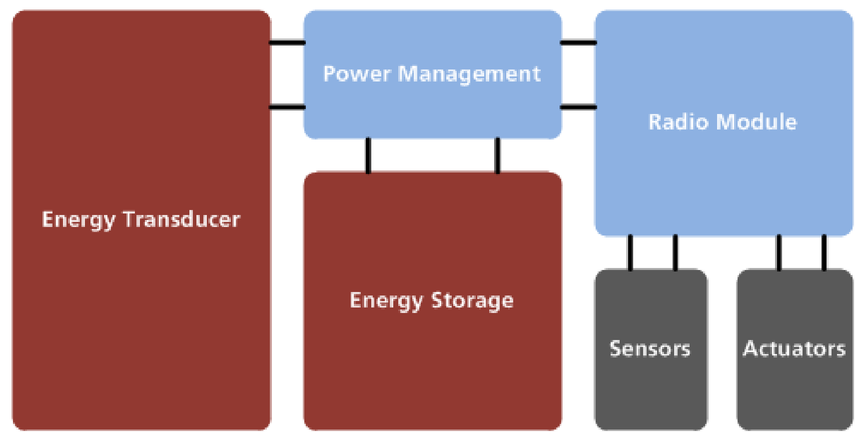
1. DC-DC converters
2. Ultra-low voltage start-up circuits
3. Bipolar inputs stages
4. MPPT implementations
5. **Micro-battery management circuits**
6. Application examples

Micro-Power Management
Micro-Battery Management Circuits

- Energy transducer
- Power management
- Energy storage



- Storage device is essential to collect small amounts of energy until a given action can be powered
- Energy transducers have a high internal resistance and cannot provide high pulse currents, e.g. for wireless transceivers



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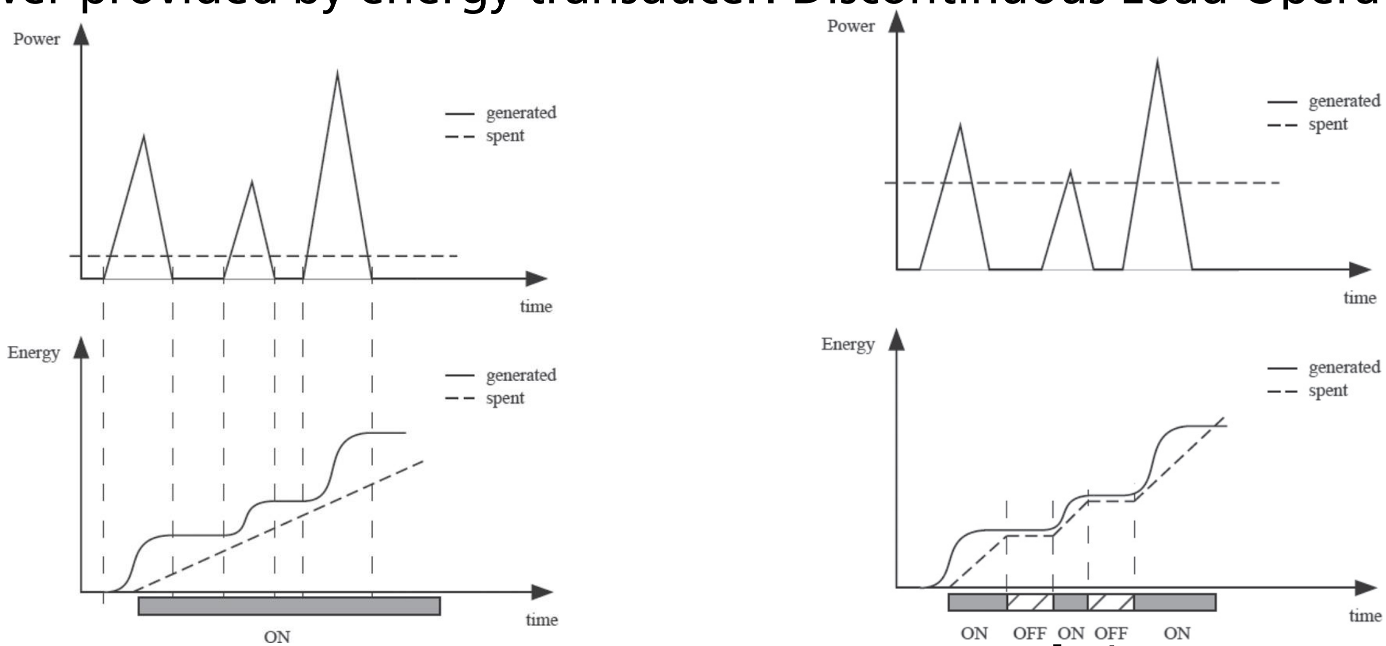
Micro-Power Management
Micro-Battery Management Circuits

- Average power consumption of application is lower than average power provided by energy transducer: Continuous Load Operation
- Average power consumption of application is higher than average power provided by energy transducer: Discontinuous Load Operation



[spies, mateu, pollak 2015]

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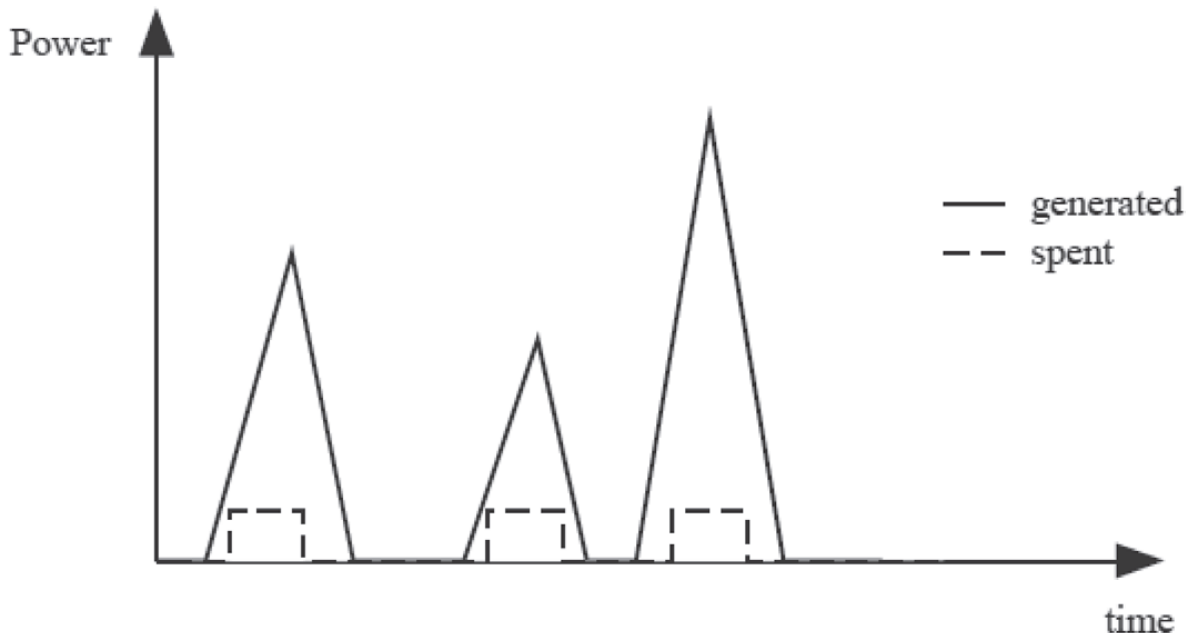
Micro-Power Management
Micro-Battery Management Circuits

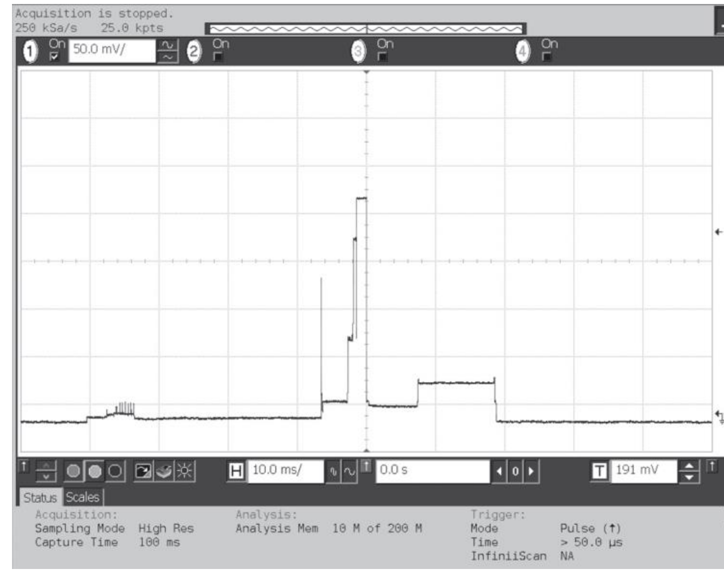
- Operation only when power is generated: No (big) storage is needed



[spies, mateu, pollak 2015]

Micro-Power Management
Micro-Battery Management Circuits

- Power consumption of load in active mode (pulse currents) will determine the energy storage element
- Fixed by electrical components and supply voltage
- Consider also enable times (transition from one operation mode to another)



Data rate: transmission speed in Kbps,

D: data bytes to transmit

n: data bytes of one packet

packet length: number of bytes that are transmitted

$$T_{active} = \frac{1}{\text{data rate} \times \frac{1\,\text{byte}}{8\text{bits}} \times \frac{1}{\lceil \frac{D}{n} \rceil \text{packet length}}}$$

[spies, mateu, pollak 2015]

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Micro-Power Management
Micro-Battery Management Circuits

- Applications with several transmission per second, average current needed / required can be calculated
- Depending on use-case, fixing average current is determined by requirement and harvester size can be calculated with ambient conditions

$$\langle I \rangle = \frac{(I_{\text{sleep}} T_{\text{sleep}} + I_{Tx} T_{Tx})}{T_{\text{sending}}}$$

$$T_{\text{sleep}} = T_{\text{sending}} - T_{Tx}$$

[spies, mateu, pollak 2015]

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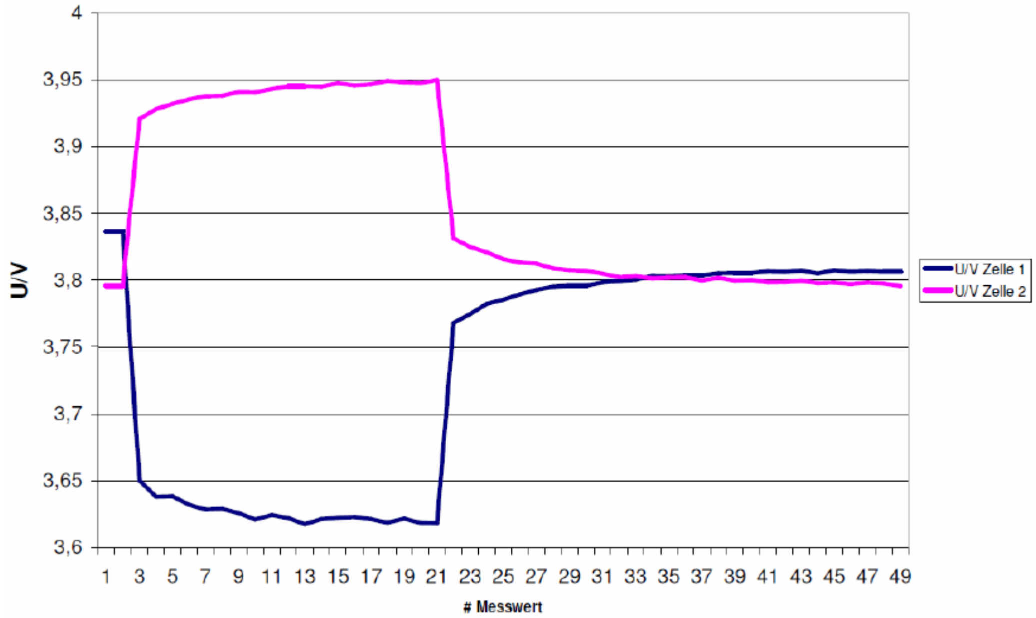
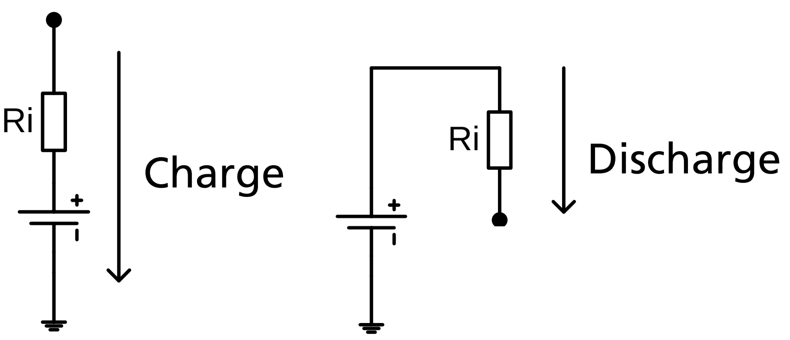
Micro-Power Management
Micro-Battery Management Circuits

- Resistance of energy harvesting transducer
- Can not provide pulse currents for e.g. transmissions
- Resistance of batteries as well
- Combine battery (if any) with capacitor





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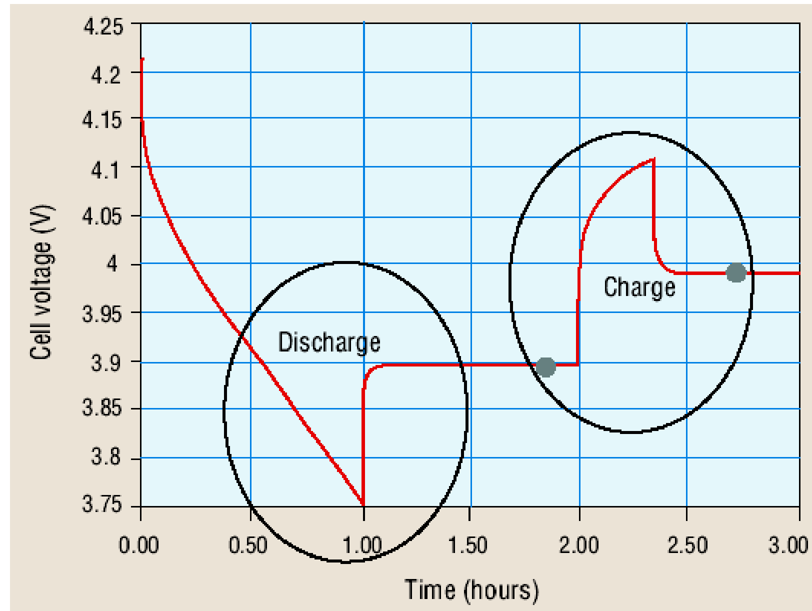
Micro-Power Management
Micro-Battery Management Circuits

- Batteries have a transient behavior: Relaxation time
- Depends on capacity size and battery chemistry
- Occurs after charging and discharging



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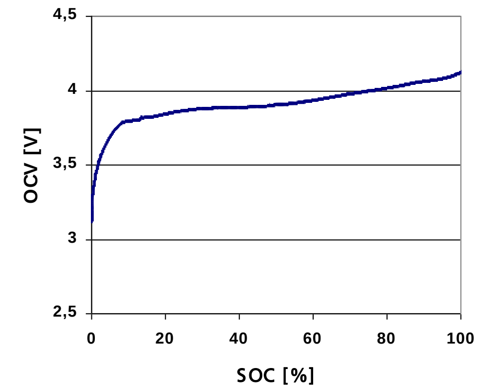
Micro-Power Management
Micro-Battery Management Circuits



- Batteries
  - Gravimetric and volumetric energy density is superior
  - Flat voltage profile between 20 and 80 % of charge level
  - Batteries have aging, loss of capacity and increase of internal resistance over time and charge cycles
  - Temperature range limited (e.g -10 - + 50° C)
  - Aging and self-discharge is a function of temperature (careful with TEG applications!!)
- Capacitors
  - Linear decrease of output voltage: Buck-boost converter needed to use complete energy

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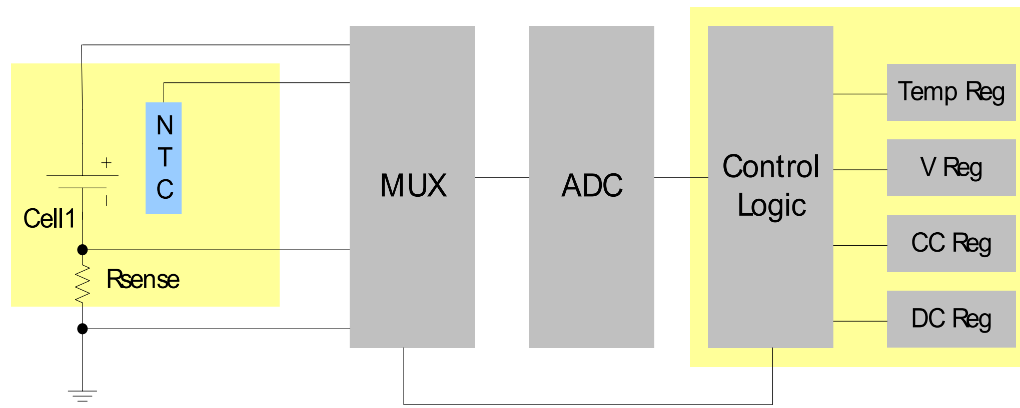
Micro-Power Management
Micro-Battery Management Circuits

- **„Coulomb-Counter“:** Measurement of charge- and discharge current
- Difference of integrated charge (CC) and discharge current (DC) is used as capacity estimation
- Full charge-discharge cycle is required to calibrate the system („Capacity Learning“, SOH estimation)



$$SOC := SOC(t) = SOC_0 + \frac{1}{C_N}\int_0^T i(t)\,dt$$

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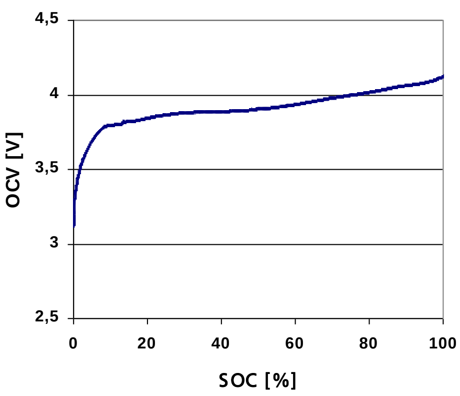
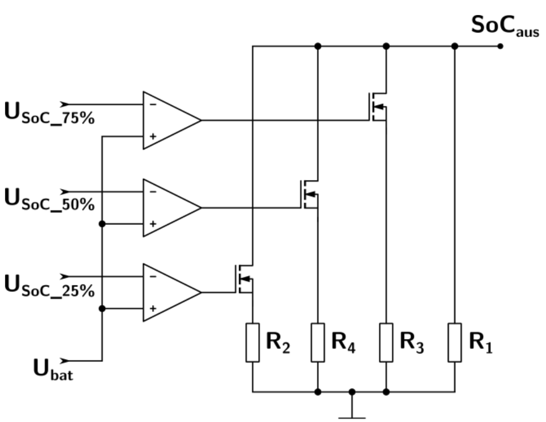
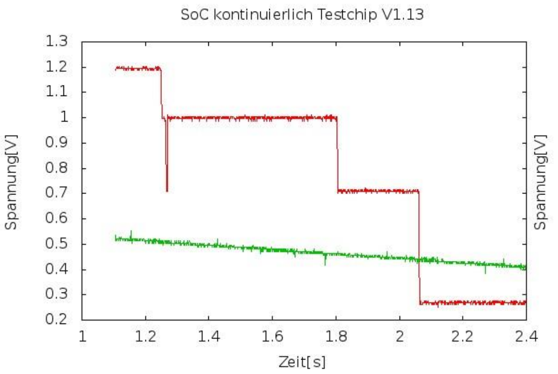
Micro-Power Management
Micro-Battery Management Circuits

- For estimation of remaining capacity (SOC – State-of-Charge), current integration is used (e.g. EVs, HEVs)
- For small batteries and energy harvesting, this is consuming too much power
- Simple SOC-estimation by measurement of open circuit (cell) voltage (OCV – Open Cell Voltage) and comparison with reference voltages







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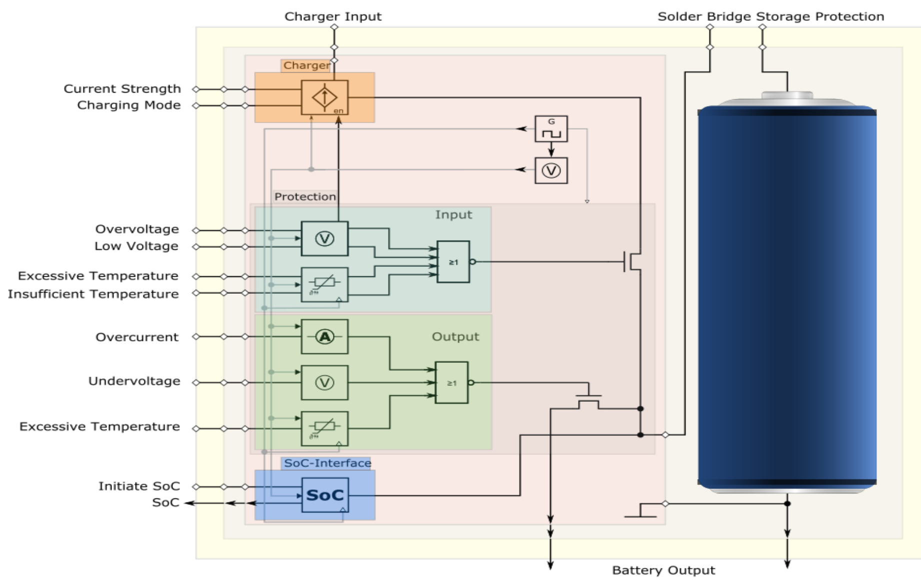
Micro-Power Management
Micro-Battery Management Circuits

- Besides monitoring, protection and charge regulation has to be carried out by the battery management system (BMS)
- BMS can work alone (hard-wired) or be controlled by µC (available in most applications of micro batteries)



Micro-Power Management
Agenda

1. DC-DC converters
2. Ultra-low voltage start-up circuits
3. Bipolar inputs stages
4. MPPT implementations
5. Micro-battery management circuits
6. **Application examples**

Micro-Power Management
Application Examples: Industrial Sensors

- Thermal gradients to power industrial wireless sensors
- Applications sensors measure temperature, humidity, vibration, gas etc.
- Bipolar gradients due to hot or cold surfaces
- 200 µW in 36 cm^3 with 2 K thermal gradient due to optimized power management
- Self-powered operation of Bluetooth LE with one transmission per second

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Micro-Power Management

Application Examples: Water Management

- Autonomous water sensor with wireless interface
- Thermoelectric generator and optimized power management
- in cooperation with Fraunhofer IZM in the Micromole-Project
- 2K thermal gradient produces typical output power of 200 µW
- Sensors: pH and conductivity (application specific customization possible)

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Micro-Power Management
Application Examples: Wearables

- Wristband with Bluetooth Low Energy connection
- Power supply covered with thermo-generator and Fraunhofer dc-dc converter
- Ca. 150 µW from 2-3 K thermal gradient
- BLE duty cycle: 1/s
- Sensor data: Temperature and acceleration, others possible
- Areas of application: Watches, medical sensors, wireless sensors
- Customization to different requirements (power output, size, integration) possible

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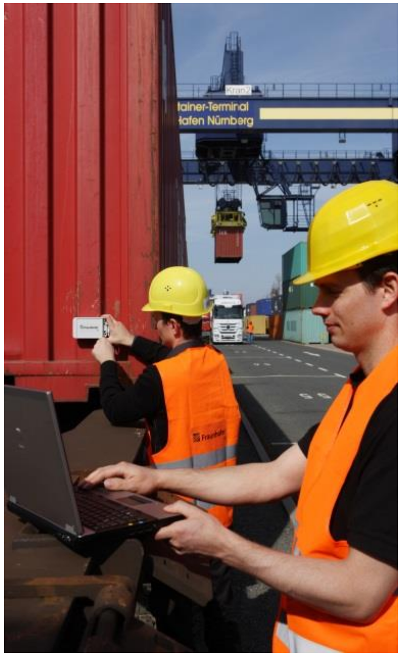
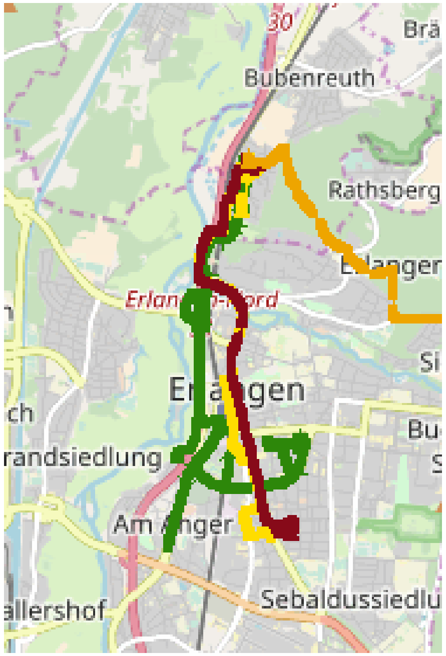
Micro-Power Management

Application Examples: Self-powered Tracking Tag

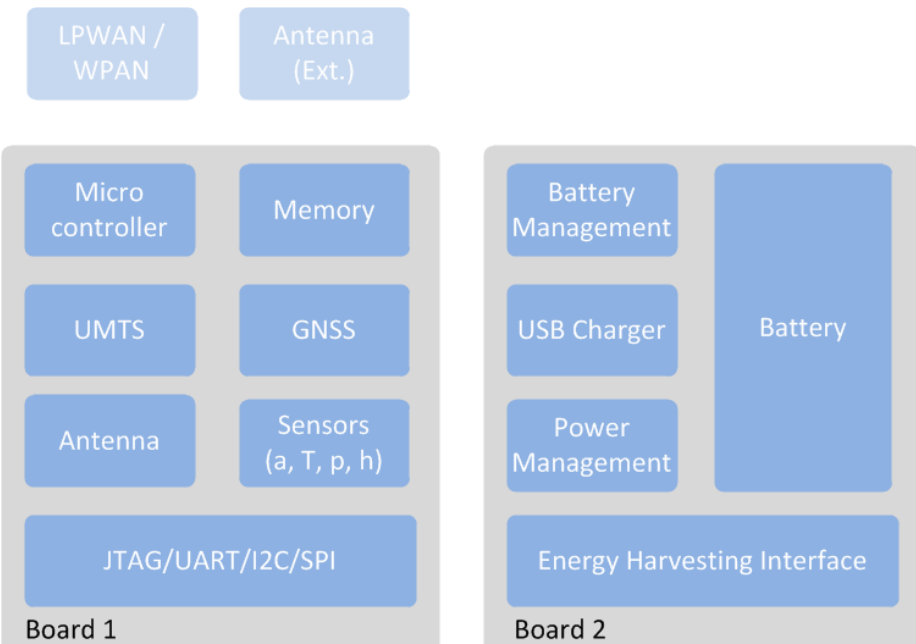
- Tracking systems for localizing expensive goods, assets, vehicles
- Measure and transmit position and other data
- Power supply is bottleneck for long-life applications (months, years)
- Vibrations are available in all moving objects, solar and thermal harvesters are optional

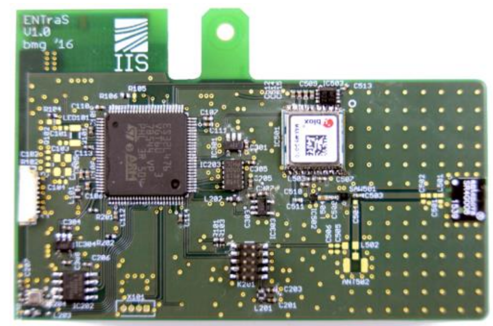




Micro-Power Management
Application Examples: Self-powered Tracking Tag

- Hardware, power consumption





Mode	Positions / Day	UMTS / Day	Power [mW]	Area Solar [cm*cm]
1	2	1	2,5	7 [z.B. 3*3]
2	6	2	3,5	10 [z.B. 3*4]
3	12	12	9	26 [z.B. 5*6]
4	24	24	17	47 [z.B. 6*8]

Micro-Power Management
Application Examples: Oval Wheel Counter

- Oval wheel counter (flow meter) exhibits inductive generator
- By rotating the oval wheels, electrical energy is produced (20 mW at 50 l/min)
- Electrical energy powers measurement electronics and wireless radio (cellular) for data transmission
- Project partner Bopp & Reuther Messtechnik GmbH und WIKON GmbH

Micro-Power Management
Summary

- Power management is the interface between transducer, storage and application
- It can loosen the requirements to both other components
- MPPT can make sense, depending on power level and dynamics of environment
- Storage device and related circuitry is mandatory in all applications to provide pulse currents
- Integration level (chip, multi-chip, discrete PCB) is often not yet an issue in present applications
- Cost is an issue, so high efficiency of power management can shrink harvester size requirements

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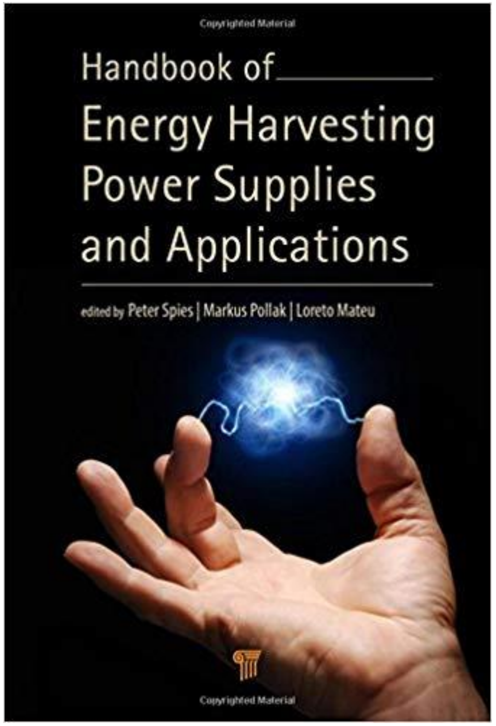
Micro-Power Management
Summary

- [spies, mateu, pollak 2015]: Handbook of Energy Harvesting Power Supplies and Applications, Pan Stanford Publishing 2015
- Thanks to my colleagues Markus Pollak and Loreto Mateu for working on this book



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Micro-Power Management
Summary

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  - MicroMole: This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 653626
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Thank you for your interest!

Any questions?

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