An introduction to energy harvesting and micro-power management

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Outline

• Introduction to energy harvesting transducers
• Techniques and trade-offs in micro-power management circuits
• Evolution and trends in power management circuits
• Case Studies (depending on time)
Introduction to energy harvesting transducers
Energy harvesting: what applications?

**Smart clothing:**
A small wearable antenna collects energy from electromagnetic waves

**Body-powered devices:**
Battery can be replaced with PV cells, thermoelectric generators that harvests energy from light and human body heat.

**Smart shoes:**
Vibrations can be used for powering small systems such as wireless pedometer.

M. Dini et al., A fully autonomous integrated RF energy harvesting system for wearable applications, EuMW 2013

V. Leonov, C. Van Hoof, R. Vlcers, Thermoelectric and hybrid generators in wearable devices and clothes, BSN 2009, 6th Workshop on Body Sensor Networks,

Energy harvesting: what applications?

- Smart home/cities/objects
- ‘True’ Internet-of-Things
- Roadmap towards trillion (connected) sensors → The ‘Abundance’

J. Bryzek, Emergence of Trillion Sensors Movement, IEEE MEMS, 2014

(source: http://www.greenpeak.com)
Energy harvesting: what applications?

- Industrial machinery
- ‘Smart’ rotating parts
  - Reliability / monitoring
  - Improved control
- Inaccessible sensor nodes
Market Trends

- The energy harvesting market is growing slower than predicted
  - Power from miniature source is actually very low, in the order of µW
  - Larger batteries are still cheaper than energy transducers
  - Applications and circuits (sensors, RF transceivers, power converters, etc.) are thought for operating with batteries and not in extreme power- and voltage- constrained scenarios

IDTechEx, Energy Harvesting Europe 2010

EETimes, 2016
The Bad

Energy Storage Sources Projections

- Gene’s law does not apply to analog sensing and transmission (slower decrease)
- Energy storage density increases only ~1.5x/decade (~1.04x/year)

The Good

Gene's Law:
Power dissipation will decrease by half every 18 months

The energy per bit per computation decreases according to the technology trend
(Gene’s law: energy/bit ~1.6x/year)


(G. Frantz, SoC in the new Paradigm of IC technology, IEEE Consumer Electronics Society – Dallas Chapter, Aug 2008)
Electromagnetic Energy Harvesters

- An electromagnetic harvester
  - is basically modelled as a mass/spring system, with a coil and a magnet
  - the housing is subject to vibrations
  - exploits electromagnetic induction
Electromagnetic energy harvesters

- **Perpetuum**[^1] energy harvester
  - Frequency tuned on mains frequency 50/60 Hz BW<1Hz
  - Output power up to 20 mW
  - Diameter: 68 mm, height: 63.3 mm

- **Enocean motion energy** harvester[^2]
  - Used for wireless light switches
  - Dimensions: 29 x 19 x 7 mm$^3$
  - Energy output: 200 µJ @2V

- **MEMS realizations**[^3]
  - 0.1 cm$^3$ volume
  - 23 nW output power @1g @9.83 kHz
  - electrodeposited copper coil

[^1]: Perpetuum Ltd., http://www.perpetuum.com
Piezoelectric transducers

- **Common materials:.getAbsolutePath()
  - **PZT** (Lead Zirconate Titanate) is a ceramic material with a high coupling coefficient $k$. The material is rigid, fragile, and contains lead.
  - **PVDF** (Polyvinylidene fluorid) is a polymeric material with a lower $k$. It’s non-toxic, bendable and can resist high shocks or impacts.

- **Typical frequencies**: from few to hundreds Hz

**Commercial piezoelectric transducers**

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Material</th>
<th>Cap. per area [F/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIEZO SYSTEMS Q220-A4-503YB</td>
<td>Ceramic material</td>
<td>12.2 nF/cm²</td>
</tr>
<tr>
<td>MIDE VOLTURE V25W</td>
<td>Ceramic material</td>
<td>8.56 nF/cm²</td>
</tr>
<tr>
<td>MEAS - SPEC. DT SERIES PIEZO (DT1-028K)</td>
<td>Meas-spec piezo film</td>
<td>380 pF/cm²</td>
</tr>
<tr>
<td>MEAS - SPEC. MiniSense 100</td>
<td>PVDF</td>
<td>254 pF/cm²</td>
</tr>
</tbody>
</table>
Equivalent Electromechanical Circuits

• In general, the above simplified models are valid for weakly electro-mechanically coupled vibrational transducers
  – i.e. when perturbations on the electrical port (e.g. power converter) produce negligible perturbations on the mechanical domain

• A more accurate model involves the use of equivalent electromechanical circuits
  – Lumped parameters, suitable for joint simulation with circuits, still some limitations (more accurate around resonance, accounting for a single vibration mode, etc.)
Equivalent electromechanical circuits

- **Electro-mechanical analogy**

<table>
<thead>
<tr>
<th>Mechanical Resonant System</th>
<th>Electric Series Resonant Circuit (Maxwell’s analogy)</th>
<th>Electric Parallel Anti-resonant Circuit (Firestone’s analogy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F = M \frac{d\dot{u}}{dt} + c_v \dot{u} + k_s \int \dot{u} dt$</td>
<td>$V = L \frac{di}{dt} + Ri + \frac{1}{C} \int idt$</td>
<td>$I = C \frac{dv}{dt} + Gv + \frac{1}{L} \int v dt$</td>
</tr>
<tr>
<td>$F$, Exerting Force (N)</td>
<td>$V$, Voltage Generator (V)</td>
<td>$I$, Current Generator (A)</td>
</tr>
<tr>
<td>$M$, Mass (Kg)</td>
<td>$L$, Inductance (H)</td>
<td>$C$, Capacitance (F)</td>
</tr>
<tr>
<td>$c_v$, Viscous coeff. (N·m/s)</td>
<td>$R$, Resistance (Ω)</td>
<td>$G$, Conductance (S)</td>
</tr>
<tr>
<td>$(k_s)^{-1}$, Elastic Compliance (m/N)</td>
<td>$C$, Capacitance (F)</td>
<td>$L$, Inductance (H)</td>
</tr>
<tr>
<td>$\dot{u}$, Velocity (m/s)</td>
<td>$i$, Current (A)</td>
<td>$v$, Voltage (V)</td>
</tr>
<tr>
<td>$f$, Force (N)</td>
<td>$v$, Voltage (V)</td>
<td>$i$, Current (A)</td>
</tr>
<tr>
<td>$\frac{1}{2}M\dot{u}^2$, Kinetic Energy (Kg·m²/s²)</td>
<td>$\frac{1}{2}L_i^2$, Magnetic Energy (H·A²)</td>
<td>$\frac{1}{2}Cv^2$, Electrostatic Energy (F·V²)</td>
</tr>
<tr>
<td>$\frac{1}{2}k_s\dot{u}^2$, Elastic Energy (N·m)</td>
<td>$\frac{1}{2}Cv^2$, Electrostatic Energy (F·V²)</td>
<td>$\frac{1}{2}L_i^2$, Magnetic Energy (H·A²)</td>
</tr>
<tr>
<td>Power=$f\cdot\dot{u}$ (W=N·m/s)</td>
<td>Power=$v\cdot i$ (W=V·A)</td>
<td>Power=$i\cdot v$ (W=A·V)</td>
</tr>
<tr>
<td>Complex Power $F\cdot\dot{u}$ (N·m/s)</td>
<td>Complex Power $v\cdot i$ (V·A)</td>
<td>Complex Power $i\cdot v$ (V·A)</td>
</tr>
<tr>
<td>Impedance=$F/\dot{u}$ (N·s/m)</td>
<td>Impedance=$v/i$ (Ω=V/A)</td>
<td>Admittance=$i/v$ (S=A/V)</td>
</tr>
</tbody>
</table>

Equivalent Electromechanical Circuits

- Example: for a vibrational piezoelectric harvester

\[
F = k_{PE} \cdot z + \alpha \cdot V
\]
\[
I = \alpha \dot{z} - C_0 \dot{V}
\]
\[
m\ddot{y} = m\ddot{z} + k_{PE}z + \alpha V + b_m\dot{z}
\]

- Example: for a vibrational electromagnetic harvester

\[
V_\infty = \alpha \cdot \dot{z}
\]
\[
F_e = \alpha \cdot i
\]
\[
V = f(i)
\]
\[
V_\infty = L_{COIL} \frac{di}{dt} + R_{COIL}i + f(i)
\]
\[
m\ddot{z} + b_m\dot{z} + F_e + kz = -m\ddot{y}
\]
RF Energy Harvesting

- RF carriers can be rectified in order to store locally energy
  - **Rectenna** = rectifying antenna
  - Matching network must be designed according to the expected input power

- Simplified representation:
  - $R_{EQ}$
  - Several kΩ
  - $V_{OC}$
  - Typically few hundreds mV

V-I and P-I transfer characteristics
Thermal energy harvesting

- Thermoelectric generators (TEG) exploit the Seebeck/Peltier effect by deploying arrays of thermocouples, thermally in parallel, and electrically in series.
- Temperature gradients and the corresponding heat flow produce voltage.
- Equivalent circuit:
  - Electrical part: $(V, I)$
  - Thermal part: $(\Delta T, \dot{q})$

ΔT is the temperature difference between hot side \((T_H)\) and cold side \((T_C)\).

* Temperature difference between hot side and ambient temperature.

<table>
<thead>
<tr>
<th>Manufacturer - Product</th>
<th>Size [mm]</th>
<th>(V_{\text{OUT}}[V]) ((\text{matched load}))</th>
<th>(P_{\text{MAX}}[W]) ((\text{matched load}))</th>
<th>Power density [W/cm(^3)/K]</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eu. Thermodynamics - GM200-449-10-12</td>
<td>(WxL=54x57) (H=3.8)</td>
<td>11.4 @ (\Delta T=170K)</td>
<td>14.6 @ (\Delta T=170K)</td>
<td>7.34e-3</td>
<td>Standard</td>
</tr>
<tr>
<td>Eu. Thermodynamics - GM200-127-10-15</td>
<td>(WxL=30x30) (H=3.7)</td>
<td>4.14 @ (\Delta T=170K)</td>
<td>2.72 @ (\Delta T=170K)</td>
<td>4.80e-3</td>
<td>Standard</td>
</tr>
<tr>
<td>Nextreme - PG8005/6</td>
<td>(WxL=11.2x10.2) (H=1.1)</td>
<td>0.85 @ (\Delta T=50K)</td>
<td>0.13 @ (\Delta T=50K)</td>
<td>2.07e-2</td>
<td>Thin film</td>
</tr>
<tr>
<td>Micropelt - MPG-D751</td>
<td>(WxL=4.2x3.35) (H=1.09)</td>
<td>2.33 @ (\Delta T=30K)</td>
<td>13.6e-3 @ (\Delta T=30K)</td>
<td>2.96e-2</td>
<td>Thin film</td>
</tr>
<tr>
<td>GreenTEG – gTEG B*</td>
<td>(WxL=7.1x7.1) (H=0.63)</td>
<td>0.388 @ (\Delta T=37K)</td>
<td>178e-6 @ (\Delta T=37K)</td>
<td>1.51e-4</td>
<td>Thin film</td>
</tr>
</tbody>
</table>
Photovoltaic Energy Harvesting

Miniature commercial devices and emerging technologies

• Sanyo amorphous silicon PV cells (e.g. AM1407)
  – Optimized for indoor fluorescent light (40-1000 Lux)
  – Output power (AM-1407) ≈ 100 µW (indoor FL light, 240 Lux)

• Ixys® PV module in tiny SMD packages (e.g. CPC1822)
  – Output power ≈ 100 µW at direct sunlight (6000 Lux)

• DSSC - Dye synthesized solar cell [1]
  – Photoelectrochemical system (no silicon)
  – Can be flexible and transparent
  – Growing efficiency (up to 15% [2])

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Towards MEMS Energy Harvesters

- The current trend is to **further shrink down** energy transducers thanks to MEMS technologies or wafer-level processing (output power also scales!)

**Electromagnetic**
- 0.1 cm$^3$, 23 nW @1g @9.83 kHz
- electrodeposited copper coil
- (Tyndall Institute, Univ. Southampton)

**Piezoelectric**
- 200 nW @0.5g @400 Hz
- 16 mm$^2$, deposited AlN
- (FBK, Delft Univ. Tech, Munich Univ. Tech.)

**Thermoelectric**
- 6-20 mV/K, 2-10 Ω
- 3-9 mm$^2$, 8-16 uW @1K
- thin film semiconductor, thermally conductive AlN ceramics
- Laird Technologies eTEG
Nano-Power Micro-Motes

CubeWorks micro-sensing nodes

University of Michigan Micro-Motes M³

http://cubeworks.us/

Current and Future Power Sources

- solar panels, micro wind turbines, miniature mechanical generators (consolidated)

- cm-sized energy harvesting transducers: piezoelectric, electromagnetic, thermoelectric, RF, small-sized PV (present)

- MEMS devices, CMOS on-chip photodiodes, microfabricated thermoelectrics (mm-sized devices) (near future)

- bio-potentials, heart beat, nanowires (piezo, PV, thermal) (future?)
Components of an Energy Autonomous System

- **Energy generation:**
  - Energy Harvesting: “transducers” making energy available from correlated or uncorrelated sources of energy
  - Energy Storage: Any kind of energy storage element that could be used to accumulate energy in excess from the harvester (e.g. batteries, (super)capacitors, etc.)

- **Energy conversion, management and distribution.**
  - any energy conversion system that trades and optimizes the energy flow from the Energy Generation block, to the user load, from/to the energy storage

- **Energy Consumption**
  - Data acquisition, elaboration, storage and transmission.
Techniques and design trade-offs for power management circuits

Maximizing the extracted power
Maximum Power Transfer

- The theorem of maximum power transfer states that the power transferred from a source to a load is maximized when $Z_L = Z_S^*$
  - where $Z_S = R_S + jX_S$ is the source impedance and $Z_L = R_L + jX_L$ is the load impedance

- For a linear source, in the maximum power condition (MPP):
  - $V_L = V_{OC} / 2$
  - $P_L = V_L^2 / R_L = V_{OC}^2 / 4R_L$
Power Transfer Characteristics

- The static I-V curves are a convenient way to describe the properties of a source in view of the design of the power converter
  - All curves combining two parameters among (P, V, I, R_L) are equivalent: P=VI, V=R_LI
  - NOTE: reactive behaviour is not accounted for
- For a linear load, the MPP is located at 50% of \( V_{OC} \)
- For a PV cell, the MPP is located around 70-80% of \( V_{OC} \)
- In order to extract all the available power, a power converter should draw from the source a current that keeps its output voltage in proximity of the MPP
- I-V curves are also useful to estimate other features of the source (e.g. rise time, etc.)
MPPT for DC sources

- $P_{OUT}$ depends on both the source condition and on the output current, and...
- …yes, there is a maximum! (MPP).

- Fractional open-circuit voltage MPPT technique (FOCV): good compromise between power spent and extracted
  - For each type of source the MPP roughly occurs when the source voltage equals a fixed fraction of the open-circuit voltage (e.g. 75% for PV, 50% for linear sources)
  - A DC/DC converter can switch so as to keep the source around this voltage
  - The reference voltage should be periodically refreshed based on OCV
  - …yes, it’s suboptimal but consumes little energy
Piezoelectric Sources

- Let us now consider the simplified equivalent circuit of a piezoelectric transducer.
- A rectifier is the simplest circuit for extracting power, but has limited and variable efficiency.
- What if we applied the matched load (i.e., an unrealistically big L)?
  - An ideal voltage source would seem to provide infinite power!
  - **NOTE**: some parameters were neglected (series resistance, electromechanical parameters, etc.).
- The message is that much higher power might still be available than with a purely resistive load.

\[
C_P = 50 \text{ nF}, \quad C_O = 10 \mu \text{F}, \quad L = 10 \text{ mH}, \quad R = 10 \Omega, \quad V_P = 5 \text{ V},
\]

Diagram:
- Simplified equivalent circuit
- Power transfer characteristics
- Efficiency

- Graph showing the relationship between \( V_O / V_P \) and \( \eta_R \) for different values of \( \gamma \).
Rectifiers for AC Piezoelectric Sources

- Rectifiers are quite common in piezoelectric energy harvesting
- Simplest available electronic interface
- However
  - limited angle of conduction
  - does not match imaginary part of source impedance

Synchronous Electric Charge Extraction for AC Piezoelectric Sources

- Piezo transducers are (low-frequency) AC sources with maximum energy achieved only twice per period
- **Synchronous Electric Charge Extraction (SECE) technique**: Two resonant circuits can be used to remove charge from the transducer: L-C<sub>P</sub> and L-C<sub>O</sub>
- Electrical charge is extracted in correspondence of maximum and minimum voltages → **very low duty cycle** (<1%) → very low consumed energy
Efficiency of SECE

- SECE uncouples the source from the load \( \Rightarrow \) efficiency almost constant
- It converts energy only when available (tracks maxima) \( \Rightarrow \) suitable for irregular vibrations
- The peak-to-peak voltage on the transducer gets doubled \( \Rightarrow \) Energy per cycle increases
- Phase 1 has constant duration and then constant efficiency
- Phase 2 has variable duration \( \Rightarrow \) variable efficiency

The rectifier interface is outperformed by SECE
(when electromechanical coupling is low)

Synchronized Switch Interfaces

- A passive rectifier has a limited angle of conduction
  - i.e. conduction starts when the source voltage is greater than the output voltage, and stops at maximum elongation when the generated current changes its sign.
  - Electrical charge generated by the transducer outside this period is not collected on the output.

- **Synchronized-Switch Harvesting on Inductor** (SSHl) consists in:
  - an inductor L in series with an electronic switch connected in parallel with the piezoelectric element.
  - The electronic switch is briefly turned on when the mechanical displacement reaches a maximum or a minimum.
  - The switch is turned off after a half electrical period, resulting in a quasi-instantaneous inversion of V.
  - V is brought on the opposite boundary of conduction of rectifier.

- Many variations have been presented in literature.

SECE/SSHI-induced Damping for AC Piezoelectric Sources

• In AC, SECE/SSHI apply a periodic series of current pulses to the transducer
• The first harmonic of current drawn from the transducer depends on frequency, on capacitance of transducer and on the actual voltage amplitude

\[
I(t) = C_P V_P^* \cdot \sum_{j=-\infty}^{+\infty} \left[ \delta \left( t - \frac{T}{4} - jT \right) - \delta \left( t + \frac{T}{4} - jT \right) \right],
\]

\[
I(t) = \sum_{n=0}^{+\infty} (-1)^n \left( \frac{4C_P V_P^*}{T} \right) \sin \left( 2\pi(2n+1) \frac{t}{T} \right).
\]

\[
I_1(t) = 4 f \cdot C_P V_P^* \cdot \sin(2\pi ft),
\]

• Damping may arise as electromechanical coupling of transducer increases \( V_P^* < 2 V_{OC} \)
• Performance might drop!

A. Romani et al., IEEE Sensors J., 2013
Multi-Source Harvesting Idea

- Micro-power conversion likely to occur in discontinuous conduction
- A single time-shared inductor & multi-input boost converter

Dini et al., IEEE TPEL 2015
Bandyopadhyay et al., JSSC 2012
Romani et al., IEEE TPEL, 2014

Voltage regulation + ext. load
Techniques and design trade-offs for power management circuits

The importance of reducing intrinsic power
The power converter has efficiency $\eta$ and draws $P_{SRC}$ from the source.

The control circuits of the power converter steal an intrinsic power $P_{INT}$ (static + dynamic).

The storage capacitor has a leakage current: $P_{LEAK}$.

The voltage monitor draws a power $P_{VMON}$.

The power available for the load is: $P_{AV} = \eta P_{SRC} - P_{INT} - P_{LEAK} - P_{VMON}$

$P_{INT}$, $P_{SRC}$ and $\eta$ are correlated $\rightarrow$ trade-off based on the maximum source power.
Duty-cycled Operation

- When \( P_{\text{LOAD}} > P_{\text{AV}} \) duty-cycled operation is necessary
- Load is activated when the output voltage is between two thresholds
  - The linear or switching regulator that supplies the load requires a minimum voltage \( V_{\text{DDL}} \) for operating
  - Given the energy \( \Delta E \) required by the load per activation, the activation voltage \( V_{\text{DDH}} \) depends on \( C_{\text{STORE}} \)
- Large \( C_{\text{STORE}} \) \( \rightarrow \) large \( E_{\text{BASE}} \) \( \rightarrow \) long wake-up time
- Small \( C_{\text{STORE}} \) \( \rightarrow \) higher \( V_{\text{DDH}} \) \( \rightarrow \) higher \( P_{\text{LEAK}} \) and \( P_{\text{INT}} \), less efficient regulation
- Trade-offs are generally required!

### Energy Available for the Load

\[
\Delta E = \frac{1}{2} C_{\text{STORE}} (V_{\text{DDH}}^2 - V_{\text{DDL}}^2)
\]

### Baseline Energy

\[
E_{\text{BASE}} = \frac{1}{2} C_{\text{STORE}} V_{\text{DDL}}^2
\]
Managing The Harvested Power

- **Typical energy harvesting applications:** when the power consumed by the application is higher than the harvested power, the duty-cycle of activation must be reduced.

**Ultra-Low Power Activity Profile**

- Extended **Ultra-Low Power** standby mode
- Minimum active duty cycle
- Interrupt driven performance on-demand

*The average consumed power decreases with the duty-cycle...*

*...at least, until we reach the baseline consumption asymptotically!*

*Input power can be lower than this!*
Baseline Consumptions

• As duty cycle $\to 0$, the consumed power approaches the ‘baseline’ consumption, i.e.:
  1. The stand-by/sleep power of the application circuits (e.g. CPU, radio, etc)
  2. If the load supply is cut off, the static current of the supervisor circuit (voltage monitor)
  3. In last instance, the intrinsic power of the power converter

• The hard limit for any energy harvesting application is the intrinsic consumption of the power converter.
  – the maximum source power must be necessarily higher in order to achieve a positive power budget (i.e. to progressively store energy)

**NOTE:** keep in mind that if you want high $\eta$ and also $P_{\text{SRC}}$ close to the MPP you’ll generally have to spend higher $P_{\text{INT}}$, but in power-constrained scenarios the quantity to maximize is:

$$P_{AV} = \eta P_{\text{SRC}} - P_{\text{INT}} = \eta \eta_{MPP} P_{\text{SRC,MAX}} - P_{\text{INT}}$$

$\iff$ need for trade-offs with $\eta$, $\eta_{MPP}$ and $P_{\text{INT}}$!
Evolution & Trends in Power Management Circuits for Energy Harvesting Applications
Advantages of ICs

• **Why ASICs for energy harvesting?**
  – Very low parasitics and leakage currents → extremely low intrinsic power (at least 10x with respect to discrete components)
  – Possibility of fine tuning of all design parameters
  – Size is also reduced, but usually is not an issue (transducers, inductors and storage are usually larger than the IC)

• **What technology?**
  – No need for extreme integration: analog and power conversion circuits do not necessarily benefit from high miniaturization
  – Older processes tend to handle higher voltages and to have lower leakage currents
Commercial devices

• The “Energy harvesting” words have been often appearing in many datasheets in the last decade
• The first devices had still (relatively) high intrinsic consumption limiting the efficiency
• Most of them were basically implementing a DC/DC converter with an input rectifier for vibrational sources
• The next generation of devices implemented more specific MPPT techniques for squeezing more power out of the power source
• The latest generation target ultra-low intrinsic consumption and look forward towards 1 µW operations
Linear Technologies

- Among the first semiconductor companies with a dedicated class of products

- **LTC3588** (2010). Basically an hysteretic switching regulator from a ‘large’ input capacitor charged autonomously by the source.
  - Relatively high voltage thresholds
  - 2.7V min input voltage, ~85% efficiency, quiescent current up to 2.5 µA
  - No evident MPPT technique

- **LTC3108** (2009). An Armstrong-Meissner oscillator based on a transformer and a depletion-mode FET + an output rectifier + LDO
  - Min input voltage down to 20 mV with a 1:100 transformer
  - No MPPT
  - Relatively low efficiency

- …and many more!
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- …and many more!
TI and STM

- The TI bq255xx and the ST SPV1050 implement a buck-boost topology with FOCV MPPT (16s refresh period)
  - Best trade-off for minimizing intrinsic consumption and for ULP sources
  - Low voltage ‘cold’ start-up is performed with internal charge pumps
  - The ICs are supplied from the storage device

- **TI bq255xx**
  - cold start-up from 330mV and 15 µW
  - sustained from 100 mV and 5 µW
  - efficiency ~75%
  - OCV sampling: 400 ms every 16 s

- **ST SPV1050**
  - cold start-up from 550 mV
  - sustained from 75 mV and 2.5 µW
  - efficiency ~80%
  - OCV sampling: 256 ms every 16 s
• Typical operation

**Figure 5. Boost startup**

In the range $2.6 \text{ V} < \text{V}_{\text{STORE}} < \text{V}_{\text{EOC}}$ the voltage is boosted by the DC-DC converter. In this voltage range the SPV1050 device sets its internal impedance according to the integrated MPPT algorithm (the MPPT mode is active). The SPV1050 device will stop switching for 400 ms ($T_{\text{SAMPLE}}$) every 16 seconds ($T_{\text{TRACKING}}$). During the $T_{\text{SAMPLE}}$, the input open circuit voltage $\text{V}_{\text{OC}}$ is sampled by charging the capacitor on the MPP-REF pin. Once the $T_{\text{SAMPLE}}$ is elapsed, the DC-DC converter will start switching back by setting its own impedance such that $\text{V}_{\text{IN}}$ stays as close as possible to $\text{V}_{\text{MPP}}$ of the source. A resistor partitioning connected between the source and the pins MPP and MPP-SET has to be properly selected, in order to match the manufacturer's specs. Please refer to Section 6.4: MPPT setting on page 24 for further details.

The periodic sampling of $\text{V}_{\text{OC}}$ guarantees the best MPPT in case of source condition variations (e.g. irradiation/thermal gradient and/or temperature changes).

**Figure 6. MPPT tracking**

Once the $\text{V}_{\text{EOC}}$ threshold is triggered, the switching of the DC-DC converter is stopped until $\text{V}_{\text{STORE}}$ will decrease to $\text{V}_{\text{EOC}} - \text{EOC}_{\text{HYS}}$.

**Figure 7. Triggering of $\text{V}_{\text{EOC}}$ (BATT pin floating)**

cold start-up

FOCV sampling

source: SPV1050 datasheet
Meanwhile in scientific literature…

- **2003.** G. Ottman et al., Optimized Piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode, IEEE TPEL

- **2007.** E. Lefeuvre et al., Buck-boost converter for sensorless power optimization of piezoelectric energy harvester, IEEE TPEL
  - 85% efficiency with $P_{IN}$ 200 µW – 1.5 mW

- Similar approach as first product (rectifier + DC/DC)
Meanwhile in scientific literature...

• **2008.** D. Dondi et al., Modeling and optimization of a solar energy harvester system for self-powered wireless sensor networks, IEEE TIE
  – Use of the FOCV MPPT technique
  – Based on a ‘pilot’ power source

• **2009.** E. Dallago et al., Electronic interface for piezoelectric energy scavenging system
  – CMOS implementation of SECE
  – 700 nA quiescent current
  – 5V maximum voltage
Meanwhile in scientific literature…

- **2012.** K. Kadirvel et al., *A 330 nA energy-harvesting charger with battery management for solar and thermoelectric energy harvesting*, IEEE ISSCC
  - Nanopower implementation of FOCV MPPT
  - 150 nA quiescent current
  - Minimum $V_{IN}=330$ mV and $P_{IN}=5 \, \mu$W.
  - Efficiency $>80\%$ for $V_{IN}=500$ mV

  - All components in a single package
  - SSHI on a miniature piezo source
  - 0.5 $\mu$W consumption in active mode, 10 pW in sleep-mode
Meanwhile in scientific literature…

- **2013-2015.** M. Dini et al. (UNIBO), Developed a series of nanopower ASICs for DC, piezoelectric, and heterogeneous energy harvesting sources, IEEE TPEL, ESSCIRC, PRIME
  
  0.32 µm STM technology
  Multi-source (9 piezo&DC) with independent MPPT and shared L
  I_{DDq} ≈ 360 nA (40 nA/source)
  Efficiency up to 85%

  0.32 µm STM technology
  Implements SECE-RCI
  Separate IC/load supplies
  P_{MIN} = 296 nW (@7 Hz, 0.5V_{PK})

  0.32 µm STM technology
  FOCV MPPT for DC srcs
  Cold start-up @0.2V
  Separate IC/load supplies
  P_{MIN} = 1 µW, I_{DDq} = 300 nA

- **2015-2016.** A. Camarda et al. (UNIBO), developed an integrated ultra-low voltage dual-polarity bootstrap circuit (-8/+15 mV) based on a piezoelectric transformer

- **2016.** G. Chowdary et al., An 18 nA, 87% efficient solar, vibration and RF energy harvesting power management system with a single shared inductor, IEEE JSSC
  
  - Multi-source IC with single shared inductor
  - P_{MIN} = 25 nW, I_{DDq} = 18 nA, 87% efficiency
State of the art of nano-power PMICs

- S. Bandyopadhyay et al., A 1.1 nW energy harvesting system with 544pW quiescent power for next-generation implants, IEEE JSSC 2014

- **Features**
  - 70-100 mV input from endo-cochlear bio-potential inside ear
  - Efficiency > 53% @ $V_{DD}=0.9V$, $L=47$ uH
  - Boost converter topology with 12 Hz switching frequency
  - Trade-off between switching frequency, FET sizes and power losses carefully investigated
  - 0.18 µm CMOS
  - Cannot self-start
  - **The lowest intrinsic consumption reported up to now**
Trends: Commercial PMICs

- Two parameters analyzed: minimum start-up voltage and minimum input power
- Most effective products target today few µW and few hundreds mV power sources
- However, many environmental sources often provide less than that in their worst case
- No synchronized switch harvesters for piezo sources available up to now
Trends: Industry and Research

- Commercial PMICs stay on the ‘safe’ side
  - reliability
  - higher output current required by external circuits
- Research is keeping on pushing the limits towards lower power and voltages
  - Very good trade-offs on power can be found
  - Voltage is practically limited by $V_{GS,TH}$ (sub-100mV typically achieved by step-up oscillators)
Trends: Industry and Research

- **Sub-µW operation** is likely to be achieved in commercial PMICs in the near future as market demands more power efficient components (MCUs, radios, analog front-end for sensors, etc.)

- **Ultra-low voltage circuits** are expected to stay in a niche (lower efficiency and higher min. power), with a envisaged use for battery-less circuit start-up from fully discharged states.
• The best product and the best research work per year of introduction were found and plotted.

• A trend towards lower operating power levels is present.

• Research works are grouped in two:
  – Truly micro-power converters
  – Nano-power converters

\[\text{src: A. Romani et al., IEEE Computer, 2017}\]
Conclusions
Conclusions

• **Energy harvesting** is an exciting research field experiencing continuous advancements.

• The **micropower barrier was broken** in research. Many commercial power management ICs are becoming available. Careful designs can yield to very interesting results.

• **Energy-aware and design techniques** for operation in **power-constrained scenarios** are progressively being applied to CPUs, sensors, radios, etc. This is necessary to go further.
References


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- TI, bq25570 datasheet
- STMicroelectronics, SPV1050 datasheet
- Cypress, S6AE10xA datasheet
- Cypress, MB39C811 datasheet
- Maxim, MAX17710 datasheet
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