Energy Harvesting Transducers

Converting Ambient Energy for Life of Product Power

February 7, 2012

APEC 2012 Industry Session Presented by:

PSMA Energy Harvesting Forum

Energy Harvesting Info & Resources for the Power Electronics Industry
Energy Harvesting Transducers

• Energy harvesting transducers are the key element for converting ambient energy into electrical energy

• Many ambient energies sources can be used

• All EH transducers have unique electrical properties that must be addressed by both the energy conversion electronics and the system as a whole.
## Energy Harvesting Transducers

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Challenge</th>
<th>Typical Electrical Impedance</th>
<th>Typical Voltage</th>
<th>Typical Power Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Conform to small surface area; wide input voltage range</td>
<td>Varies with light input Low $k\Omega$ to 10s of $k\Omega$</td>
<td>DC: 0.5V to 5V [Depends on number of cells in array]</td>
<td>10µW-15mW (Outdoors: 0.15mW-15mW) (Indoors: &lt;500µW)</td>
</tr>
<tr>
<td>Vibrational</td>
<td>Variability of vibrational frequency</td>
<td>Constant impedance 10s of $k\Omega$ to 100k$\Omega$</td>
<td>AC: 10s of volts</td>
<td>1µW-20mW</td>
</tr>
<tr>
<td>Thermal</td>
<td>Small thermal gradients; efficient heat sinking</td>
<td>Constant impedance $1\Omega$ to 100s of $\Omega$</td>
<td>DC: 10s of mV to 10V</td>
<td>0.5mW-10mW (20°C gradient)</td>
</tr>
<tr>
<td>RF &amp; Inductive</td>
<td>Coupling &amp; rectification</td>
<td>Constant impedance Low $k\Omega$s</td>
<td>AC: Varies with distance and power 0.5V to 5V</td>
<td>Wide range</td>
</tr>
</tbody>
</table>

Designs must deal with different: Impedance, Voltages, Output power, etc.
Harvester Technology Priorities

- Wireless Sensor Nodes
- Industrial Performance Monitors
- Home Energy Use Monitors

DC Input (55%)

- Thermoelectric Heat, 29
- Photovoltaic Light, 91
- AC Input (42%)
- Piezoelectric - Vibration, Push Button
- Electrodynam - Rotation, Vibration, etc
- Other, 11

Start-up companies

- Universities & Research
- Tire Pressure Monitoring Systems (TPMS)
- Machine Monitoring

Fully commericalized
Small Scale Solar Powered Apps
Solar Power Conversion

- Maximum power point (MPP) is influenced by environment
  - 10μW/cm² (indoor)
  - 10mW/cm² (outdoor)
The differences: Fluorescent lighting < 1000 lux

source: TI Solar Lab

Technologies
Meso-scale Electromagnetic – Vibrational EH

• Pro’s
  ✓ Plenty of power for WS
    ▪ 40 to 100 mWatts
    ▪ Power many WS at once
  ✓ Broad bandwidth capable
  ✓ Reliability proven

• Con’s
  ✓ No vibration, no power
  ✓ Large and costly ($300+ each)
  ✓ 1-axis power generation (orientation dependent)
  ✓ **Not scalable to micro-scale (MEMS)**
    ▪ 10X reduction in size ➔ $10^4$ reduction in magnetic force $F_B$
MEMS Piezoelectric - MicroGen

patent-pending upper and lower electrode design

patent-pending piezoelectric material

patent-pending structural cantilever material

"frame"

end-mass $M$

Notes: 1. Not drawn to scale; and
2. Sixteen (16) patents and/or trade-secrets pending.
Piezoelectric Energy Creation

Power $P \sim \delta^2 \sim (m_p)^2$

$\delta = \text{deflection}$

Strain induced charge $Q \rightarrow P \sim (Q^2/C_p)$

$(C_p = \text{piezo capacitance})$
MEMS Piezo Harvester in Action

Static

Dynamic (60 Hz) –
(a) 0.5 \text{ g} \rightarrow >30 \, \mu\text{Watts}^* 
(b) 1.0 \, \text{ g} \rightarrow >120 \, \mu\text{Watts}^* 

* 2013 \rightarrow 2\times; 2014 \rightarrow 4\times

Note: Patent-pending design and material improvements will quadruple power density yielding a smaller die. This results in more die per wafer and lower production cost.
Thermoelectric Generators

• Uses hot and cold surfaces – Seebeck effect

• Performance
  – High Power
  – Mid-High Cost

\[ V = (S_B - S_A) \cdot (T_2 - T_1) \]
Harvesting Thermal Gradients

Heat energy can be found in many places

Industrial
- Motors, production robots, vacuum pumps, gear boxes, bearings (e.g. temperature & vibration monitoring)
- Wireless process automation sensors (e.g. temperature sensor, pressure sensor)

Domestic appliances
- Energy reduction for kitchen equipment (e.g. autonomous smart cooking)
**Thin Film Thermal Generators**

**TGP: Thermal Generator in Package**
- High output voltage: \( TGP-751 > 100 \text{ mV/K} \)
  - Simple & high-efficient DC-DC Booster
  - Operation from small delta \( T < 10 \text{ K} \)
- SMD component: reflow production
- Operates with discrete or 1-chip (TI bq25504) DC-DC Booster
- Easy mechanical & thermal integration

**TE-CORE: Thermal harvesting module**
- Integrated DC-DC Booster
- Fixed 2.4 V output voltage (1.8 V – 4.5 V)
- Thin Film Battery can be connected
- Starts at delta \( T < 10 \text{ K} \)
- Output power depends on heat sink type

<table>
<thead>
<tr>
<th>( T_{hot} ) [°C]</th>
<th>( U_{oc} ) [Volt]</th>
<th>Power [mW]</th>
<th>Year energy [mAh]</th>
<th>Batteries [AA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.56</td>
<td>0.36</td>
<td>2102</td>
<td>1-2</td>
</tr>
<tr>
<td>50</td>
<td>0.96</td>
<td>1.1</td>
<td>6424</td>
<td>3-4</td>
</tr>
<tr>
<td>60</td>
<td>1.4</td>
<td>2.2</td>
<td>12848</td>
<td>&gt; 6</td>
</tr>
</tbody>
</table>

*Output power indication at ambient of 25 °C*
Manufacturing Thermal Generators

- Availability thin-film thermoelectric technology
  - Micropelt factory opened June 2011
  - Semiconductor quality equivalent

- Microstructures offer high output voltage
  - 400 times more thermoelectric p-n couples compared to bulk Peltier components
    - > 100 mV / K output performance
    - efficient DC-DC Booster
    - low delta T operation possible

- Button-cell generator (TGP)
  - TGP generator outputs 100’s of μW to milliWatts and can power miniaturized sensors or actuators
  - Any engineer can create a good thermal concept
  - Suitable for standard reflow processes
Wireless Power Charging

- Light / solar energy not always sufficient
- Thermal difference not always available
- Vibration not always available
- RF-based wireless power
  - Send power over distance - μW, low mW
  - Overcomes lack of light, temp diff., or vibration
  - Controllable: continuous scheduled on demand
Using Wireless Power

• Micro-power over distance using common radio waves
  – Microwatts (μW) to low milliwatts (mW)
• Micro-power is useful for:
  – Trickle-charging batteries (μA to low mA current)
  – Powering battery-free devices
• Received power is determined by multiple factors:
  – Power of RF source
  – Distance from RF source
  – Size / performance of receiving antenna
  – Transmission frequency (e.g. 915MHz)
Wireless Power Transmitter

TX91501 Powercaster® Transmitter

- 915 MHz center frequency
- FCC and IC certified
- RoHS compliant
- DSSS modulation (power)
- ASK modulation (data)
- 1W or 3W EIRP
  - TX91501-1W-ID
  - TX91501-3W-ID
- ~60° beam pattern
- Data broadcast (factory-set)
- Plug-and-play installation
- Powers virtually unlimited number of Powerharvesters

Dimensions:
- 6.25” width
- 6.75” height
- 1.63” depth

- Power Jacks (2) – 5V
  Back – for tabletop placement
  Bottom – for wall mounting
- Status Indicator LED
  Green – Transmitting
  Red – Fault Condition

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Wireless Power Receiver

- Convert RF input to DC current
- Provide power management
- Frequency range: 850-950MHz
- RSSI and Data output
- Designed for standard 50Ω antennas

**P1110**

**Continuous Power Output**
- RF range: -5.0dBm to 20dBm
- Output voltage: 1.8V to 4.2V (configurable)
- Range of at least 3 meters

**P2110**

**Pulsed Power Output**
- RF range: -11.5dBm to 15dBm
- Output voltage: 1.8V to 5.25V (configurable and regulated)
- Range of at least 10 meters

More Info: www.powercastco.com
# Power Source Trade-offs in Sensors

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Cost</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wired Sensors</td>
<td><strong>Highest initial cost</strong>&lt;br&gt;<strong>Average operating cost</strong></td>
<td>Simple&lt;br&gt;Reliable&lt;br&gt;Very high installation cost</td>
</tr>
<tr>
<td>Battery Powered Wireless Sensors</td>
<td><strong>Lowest initial cost</strong>&lt;br&gt;<strong>Highest operating cost</strong></td>
<td>Simple&lt;br&gt;Cheaper than wired&lt;br&gt;Constant battery replacement</td>
</tr>
<tr>
<td>Energy Harvesting Wireless Sensors</td>
<td><strong>High initial cost</strong>&lt;br&gt;<strong>Lowest operating cost</strong></td>
<td>More complex engineering&lt;br&gt;Lowest lifetime costs</td>
</tr>
</tbody>
</table>
## EH Transducer Cost Effectiveness

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Typical Cost</th>
<th>Power</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>$0.20/uW</td>
<td>~1.0-1.5 V/cell</td>
<td>- Limited power output (indoors)</td>
</tr>
<tr>
<td>-Inside</td>
<td>$0.20/mW</td>
<td>10 uW/cm²</td>
<td>- Can be inconsistent</td>
</tr>
<tr>
<td>-Outside</td>
<td>$0.20/mW</td>
<td>10 mW/cm²</td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>$0.50/mW</td>
<td>~ 1 V @ 10 K</td>
<td>- Not counting heat sink size/cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 mW/(K*cm²)</td>
<td>- Reliable &amp; high power</td>
</tr>
<tr>
<td>Piezo</td>
<td>$20/mW</td>
<td>~ 25 VAC</td>
<td>- High volume pricing</td>
</tr>
<tr>
<td>-Resonant</td>
<td></td>
<td>0.1-0.5 mW/cm²</td>
<td>- Resonant: vibration at 1g</td>
</tr>
<tr>
<td>-Random</td>
<td></td>
<td>~1 uW/cm²</td>
<td>- Random: low power &amp; inconsistent</td>
</tr>
<tr>
<td>RF</td>
<td>$30/mW</td>
<td>Regulated V</td>
<td>- 3W TX w/ 6 dBi gain antenna</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 mW at 2m</td>
<td>- Low power output</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 uW at 10m</td>
<td>- Low volume pricing</td>
</tr>
</tbody>
</table>
Summary

• Energy can be harvested from the ambient environment using various transducers
• Each EH transducer needs appropriate high efficiency energy conversion electronics
• Small wireless sensors can be built with EH transducers that are becoming smaller through MEMS and miniaturization techniques
• EH transducer costs are decreasing and are now becoming an effective alternative to primary batteries.
EH-Powered Autonomous Wireless Sensor Block Diagram

Transducer
- Photovoltaic
- Thermoelectric
- Piezoelectric
- Inductive
- RF

Processor and Radio Link
- Microcontroller
- RF Wireless
- Optimized Protocol
- MCU + Radio

Energy Processing
- Power Conversion
- Energy Storage
- Power Management

Sensor
(e.g., temperature, pressure, occupancy)

Energy Storage Device