Advancements in Energy Harvesting Transducers and the Challenges they Present for Power Management Solutions

Brian Shaffer
Applications Manager
Boston Design Center
Linear Technology Corporation
bshaffer@linear.com, 978-656-3755
Outline:

• Transducers
  • Manufacturers (Advertised Products)
  • Market Challenges?
  • How Much Power is Available?
  • Power Management Challenges?

• Examples
  • Solar
  • TEG
  • Vibration

• If Energy Harvesting Alone is Not Enough…
  • Extending Battery Life with Energy Harvesting
Energy Harvesting Transducers
Manufacturers (Advertised Product)

Thermoelectric Generator or Thermopile (Heat)
- Marlow Industries (EverGen), Micropelt (TE-Power),
- Perpetua (Power Puck), Nextreme (eTEG/WPG)

Piezoelectric (Motion / Vibration / Strain)
- Mide (Volture), PI Ceramics (P-876), MicroGen (BOLT™),
- Smart Materials (M8528P2, M8557P2, M8585P2),
- T.M.S. AUTO PARTS CO LTD; alibaba.com
  (piezo bending generators)

Photovoltaic (Light)
- G24i (Indy, DOM, COM), Solar Print (SP5848 DSSC),
  Panasonic (Amorton)

Galvanic (Moisture)
- Components available to work with minimal voltages

Electromagnetic (Motion / Vibration / Induction)
- Perpetuum (PMG FSH)
Energy Harvesting Transducers

Market Challenges

Thermoelectric Generator or Thermopile (Heat)
- Approvals from Field Trials

Piezoelectric (Motion / Vibration / Strain)
- High-Volume Application to Reduce Transducer Pricing

Photovoltaic (Light)
- None – Deployed in many applications

Galvanic (Moisture)
- None – Deployed in farming operations

Electromagnetic (Motion / Vibration / Induction)
- Low-cost small disposable or re-usable transducer would enable large market in asset tracking.
Energy Harvesting Transducers

How Much Power is Available?

A comparison of ambient energy sources (before conversion). (Source: CEA-Leti).

Ambient Energy is Only Part of the Story…
Energy Harvesting Transducers
Power Management Challenges

Thermoelectric Generator or Thermopile (Heat)
- Vin Dynamic Range (20mV-200mV),
- Low Impedances (3.5Ohms),
- Higher Impedance TEGs (150-300Ohms),
- Thermal Impedance of TEG and System for desired DT

Piezoelectric (Motion / Vibration / Strain)
- AC Source Voltage, Vin Dynamic Range (4Vpp-200Vpp),
- High Source Impedance (80k-900kOhms)

Photovoltaic (Light)
- Maximum Power Point Operation

Galvanic (Moisture)
- Low Voltage, Low Impedance

Electromagnetic (Motion / Vibration / Induction)
- AC Source Voltage, Vin Dynamic Range (2Vpp-20Vpp),
- Source Impedance (4k-800kOhms)
How Much Power is Available at the LOAD?

Available LOAD power depends on:
- Energy source
- Transducer
- Power conversion efficiency

→ Each energy source needs to be quantified
→ Each source requires an optimized transducer
→ Each source requires an optimized power manager
Solar Energy Considerations

<table>
<thead>
<tr>
<th>[Light Source]</th>
<th>Sunlight</th>
<th>Fluorescent light</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition</td>
<td>Illuminance (lux)</td>
<td>Condition</td>
</tr>
<tr>
<td>Direct sun</td>
<td>100,000 to 120,000</td>
<td>Design stand (partially illuminated)</td>
</tr>
<tr>
<td>Bright</td>
<td>50,000 to 100,000</td>
<td>Office/conference room</td>
</tr>
<tr>
<td>Cloudy</td>
<td>10,000 to 50,000</td>
<td>Restaurants/coffee shops</td>
</tr>
<tr>
<td>Rain</td>
<td>5,000 to 20,000</td>
<td></td>
</tr>
</tbody>
</table>


- **Solar cell P\text{OUT}** depends on Lux (lumens / m\textsuperscript{2})
  
  (1 lux = 1.46mW of EM power at 540 terahertz / m\textsuperscript{2})

- Lux varies greatly from indoors to outdoors

- Lux easily measured with a light meter
Solar Power Management Considerations

- Series / parallel combinations optimize panel voltages
- Maximum power point tracking / control optimizes energy transfer
Solar Example #1

G24i Indoor Dye Sensitized Solar Cell (1 Volt Panel)

LTC3105
Low Voltage Boost Converter with Maximum Power Point Control (min $V_{IN}$ 250mV)

Output:
$V_{OUT} = 3.3V$
$I_{OUT} = 20uA @ 200 lux$
$I_{OUT} = 200uA @ 1000 lux$
Solar Example #2

Simple Method for Charging a Battery:

**LTC4071**
Li Ion / Polymer Shunt Battery Charging System with Low Battery Disconnect
($I_{CC} = 550nA$, $I_{BAT\_DISCONNECT} = 0.01nA$)

$V_{IN} \sim 4V$

"Output":

$V_{OUT} \sim V_{BAT}$

$I_{CHG} \sim 90uA$ @ 200 lux

$I_{CHG} \sim 450uA$ @ 1000 lux
Thermal Energy Considerations

TEGs (Thermoelectric Generators)

- VOUT proportional to temperature differential
- Need to maintain a temperature gradient across TEG
- → Heatsinks required
TEG Characteristics

- TEG open ckt voltages are very low
- TEG output impedance also very low
- TEG’s require highly specialized power management
Thermoelectric Example #1

LTC3108
Ultralow Voltage Step-Up Converter
and Power Manager
(min $V_{IN} = 20mV$)

$V_{IN} \sim 20mV - 500mV$

Output:
$V_{OUT} = 3.3V$
$I_{OUT} = 60uA \; @ \; 10^\circ C$ delta $T$
$I_{OUT} = 400uA \; @ \; 30^\circ C$ delta $T$

30mm x 30mm TEG

© 2013 Linear Technology
Linear Technology Confidential
Thermoelectric Example #2

LTC3109
Auto-Polarity, Ultralow Voltage Step-Up Converter And Power Manager
(min $V_{\text{IN}} = \pm 30\text{mV}$)

Output:
$V_{\text{OUT}} = 3.3\text{V}$
$I_{\text{OUT}} = 60\mu\text{A}$ @ $\pm 10^\circ\text{C}$ delta $T$
Vibration Energy Considerations

What does the vibration source look like?

TIME DOMAIN

FREQUENCY DOMAIN

© 2013 Linear Technology

Linear Technology Confidential
Vibration Transducers

Frequency response must match or power falls off quickly

Source: Adaptive Energy Corporation

Source: Advanced Ceramics Corporation
Vibration Source #1 – Piezoelectric

LTC3588
Piezoelectric Energy Harvesting
Power Supply
($I_{CC} = 900 \text{nA}$)

Output:
$V_{OUT} = 3.3 \text{V}$
$I_{OUT} = 200 \text{uA} \at 0.25 \text{g} / 40 \text{Hz}$
Vibration Source #2 – Electromechanical

LTC3588
Piezoelectric Energy Harvesting Power Supply
(Eff ~ 90% @ VIN ~ 5V)

PMG FSH

VIN ~ 5V

Output:
V_{OUT} = 3.3V
I_{OUT} = 400\mu A @ 0.025g !!!
If Energy Harvesting Alone is Not Enough…

Use Energy Harvesting to Extend Battery Life:

Load gets power from either indoor solar or Li primary cells (0.66% / year self discharge)

**Design Goal:**

\[ P_{out} = 25uW \text{ @ 200 lux} \]

(2.5V,10uA)
Battery Life Extender

Solar Powered Thermostat with Battery Backup

$\text{VOUT} \approx 2.5\text{V @ 10uA}$

$R_L = 250k$
Low Power EH + Battery Solutions

Solar Powered Thermostat with Battery Backup

Available Output Power:
25μW @ 200 lux

\[ V_{OUT} = 2.5V, I_{OUT} = 10μA \]

Batteries take over when light source is gone
Wireless MESH Network Example – Energy Requirement as a function of TX and Neighbors

Average Energy Consumption as a function of Tx and Neighbors

- Steady State
- 10 Sec Temp Tx
- 7 Sec Temp Tx
- 3 Sec Temp Tx
- 1 Sec Temp Tx

Energy Consumption (mA)

© 2013 Linear Technology

Linear Technology Confidential
Battery Life Extender - Basic System Block Diagram
Buck-Boost with Battery Switch-Over Circuit

@200lux, 3V, 42uA = 126uW

- 3129 switch-over circuit switches between Battery and Solar
Buck-Boost with Battery Switchover

- Here solar is barely able to supply load, As Vin drops, it hits RUN threshold, part stops switching, runs off Vbat
Extending Battery Life with Energy Harvesting

- Sanyo AM-1815 (1211)
- CR2032, 3V Lithium
Use Energy Harvesting to Extend Battery Life

- Piezoelectric and
- Primary Cell Battery

- AC1 and or AC2 to VOUT = BUCK

- BAT to VOUT = Buck-Boost
Advancements in Energy Harvesting Transducers and the Challenges they Present for Power Management Solutions

Brian Shaffer
Applications Manager
Boston Design Center
Linear Technology Corporation
bshaffer@linear.com, 978-656-3755

Thank You
# Energy Harvesting Solutions

<table>
<thead>
<tr>
<th>Energy source</th>
<th>Transducers</th>
<th>LTC Power Management ICs</th>
<th>Typical $P_{\text{OUT}}$ @ $V_{\text{OUT}} = 3.3\text{V}$</th>
<th>Maximum $P_{\text{OUT}}$ @ $V_{\text{OUT}} = 3.3\text{V}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor Solar (200lux – 1000lux)</td>
<td>Photovoltaic Cells (100cm$^2$)</td>
<td>LTC3105</td>
<td>100uW – 1mW</td>
<td>&gt;100mW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC4071</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3129</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3459</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3330</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outdoor Solar (1000lux – 50000lux)</td>
<td>Photovoltaic Cells (100cm$^2$)</td>
<td>LTC3105</td>
<td>1mW – 100mW</td>
<td>&gt;100mW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3588</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3129</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3330</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal (10°C – 30°C dT)</td>
<td>TEGs (100cm$^3$)</td>
<td>LTC3108</td>
<td>200uW – 1.4mW</td>
<td>&gt;10mW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3109</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration (Piezo: 0.1g – 1g) (EM: 0.025g – 0.5g)</td>
<td>Piezoelectric (30cm$^2$)</td>
<td>LTC3588</td>
<td>50uW – 500uW</td>
<td>&gt;100mW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3129</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3459</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>LTC3330</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

© 2013 Linear Technology

Linear Technology Confidential