Practical Design Considerations for Thermal and Photovoltaic Energy Harvesting Applications

“Free”, Unlimited, Zero Maintenance Energy…
But the Laws of Physics Still Apply

Jim Noon
Applications Engineering Section Leader– Power Products
Linear Technology Corporation
email: jnoon@linear.com

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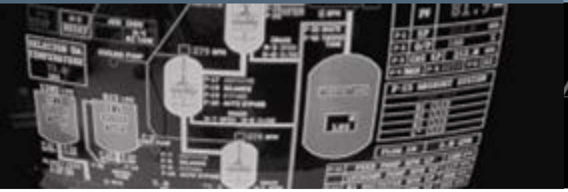

LINEAR TECHNOLOGY

Outline

- Energy Harvesting Basics
  - What are the benefits?
  - Where is it useful?
  - Design Example: Thermal Energy Powered Wireless Sensor Node
- Defining the Problem and Selecting the Right Transducer
  - Application power requirements
  - TEG models and capabilities
  - Choosing a TEG and Heatsink
  - Photovoltaic Cell characteristics and considerations
- Converting Harvested Energy into a Regulated Output
  - Boosting millivolts to volts and Energy management
  - What is MPPC?
  - Charge storage strategies and tradeoffs
- Integrated Solutions

Energy Harvesting – where is it useful?

- Wireless Sensor Networks where maintenance is costly, inconvenient or hazardous
- Coupled with a primary battery to extend battery life
- Powering sensors/nodes where line power is not available

Asset Tracking/Monitoring

Building Security, Lighting & Climate Control

Plant Automation

Remote Monitoring

Typical Application: Remote Wireless Sensors

Energy Harvesting – why all the interest?

Ambient energy is available almost everywhere

- Solar, Vibration, Thermal, RF, etc.
- Capture and use energy that is readily available and free

Harvested energy can supplement or replace existing sources

- Greatly extend battery run time
- Minimize maintenance frequency / costs
- Eliminate wiring costs

Wireless Sensors and Nodes require very low Average power

- Ultra-low power RF links and uControllers are readily available

Enabling the self-powered application…

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The Autonomously Powered Wireless Sensor Node

Power Conversion and Energy Management is the Missing Link

- Remote Industrial Sensor networks
- HVAC monitoring and control
- Building Automation
- Predictive Maintenance
- Avionics
- Automatic Metering

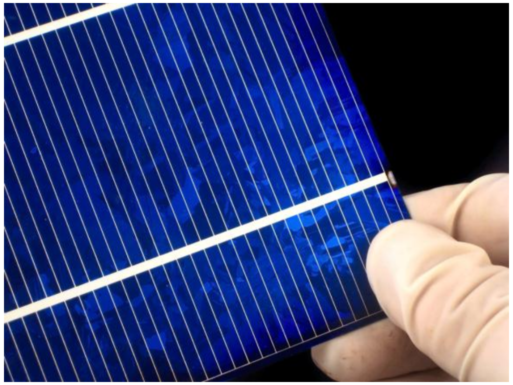
“Free” Energy Source → Energy Harvester / Manager → Sensors, A/D, UController → Wireless xmit/rcvr

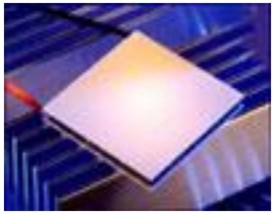
Thermal, PV, Piezo, RF…

Design Example:
Autonomously Powered Wireless Sensor Node

How can I replace these…

…with these?





Motivation: Eliminate need to replace dead batteries

Step 1: Characterize the Average Power requirements
->For typical WSN, the power needs are modest

EH-Link energy consumption levels w/ 802.15.4 radio (microJoules):

Start up energy:	12 µJ
Accelerometer:	105 µJ/measurement
Humidity (RH) sensor:	105 µJ/measurement
Wheatstone bridge:	168 µJ/measurement
Data transmission:	92 µJ/packet

Source: Microstrain Corporation

Typical Application: 3 sensor wireless monitor
Energy requirements: 482uJ total
Transmitting every 3 seconds requires ~**161uW** (482uJ / 3s)

Wireless sensor power requirements continue to drop

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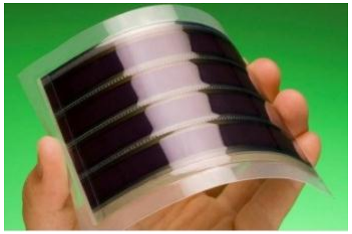
Step 2: Determine what Power Transducer can be applied

->PV and Thermal transducers can harvest ample power and are relatively inexpensive

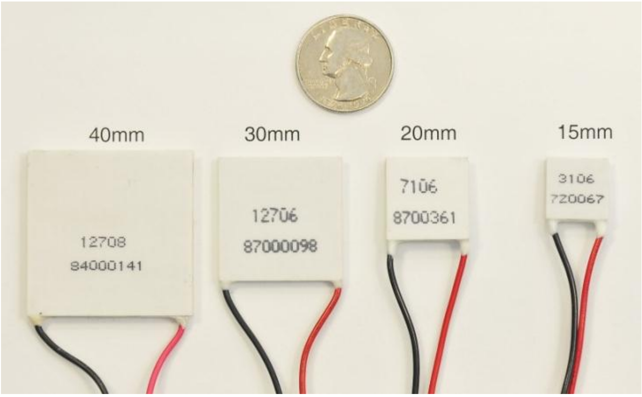


Thin Film PhotoVoltaic

Amorphous Si PhotoVoltaic

Characteristics:

- ~450mV / Cell Vout
- 10uW / cm^2 (indoor light, Thin Film cell)
- 2.9mW / cm^2 (outdoor light – complete converter)



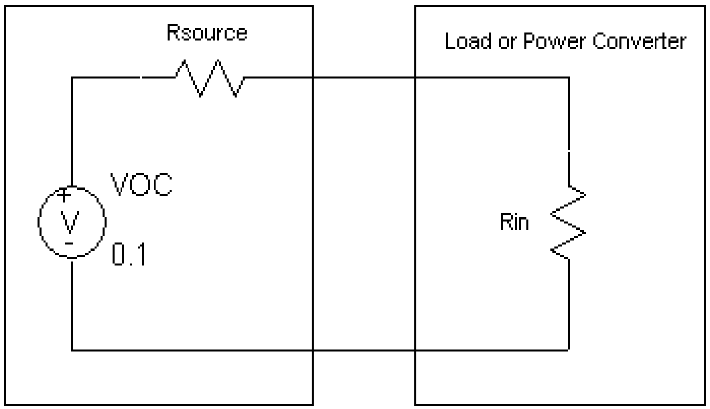
Conventional ThermoElectric Generators (TEG)

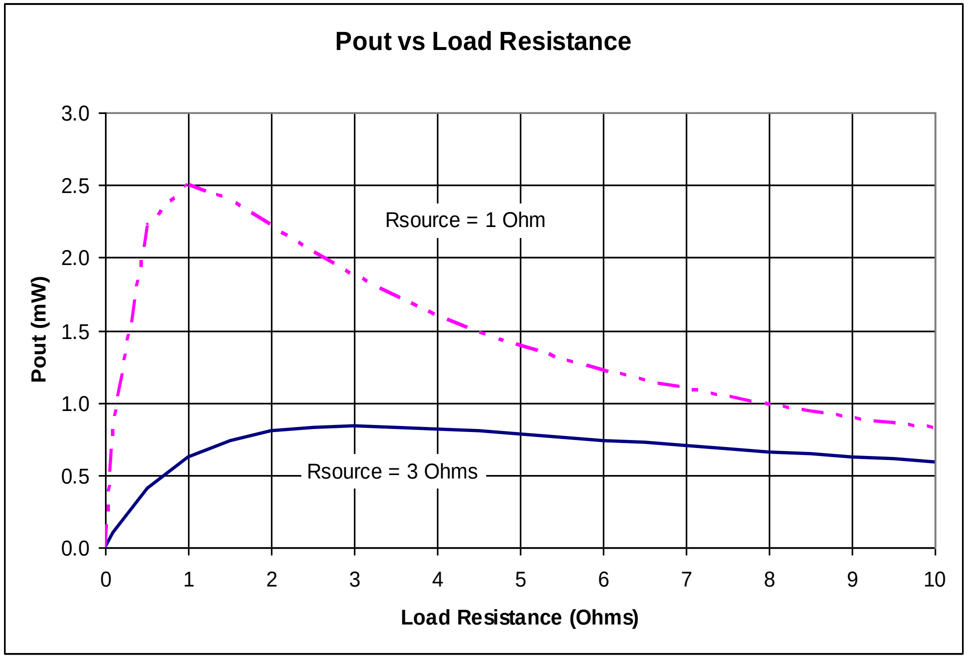
Characteristics:

- ~12mV / degree dT across TEG VOUT
- Power Out from complete converter: 1.3mW at 5 degree dT (40mm)

Q: What about Load matching and Maximum Power Point ?

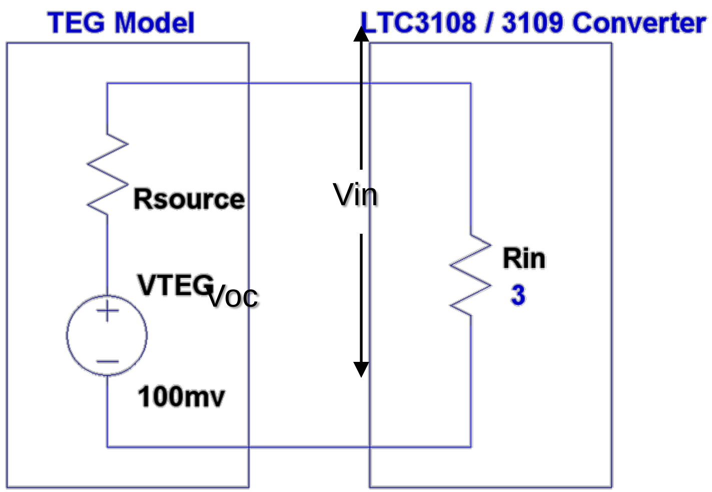
A: These are terms that refer to extracting the maximum power possible from the power source used. Regardless of the power source, this occurs if Rout(source) = Rin (converter or load)

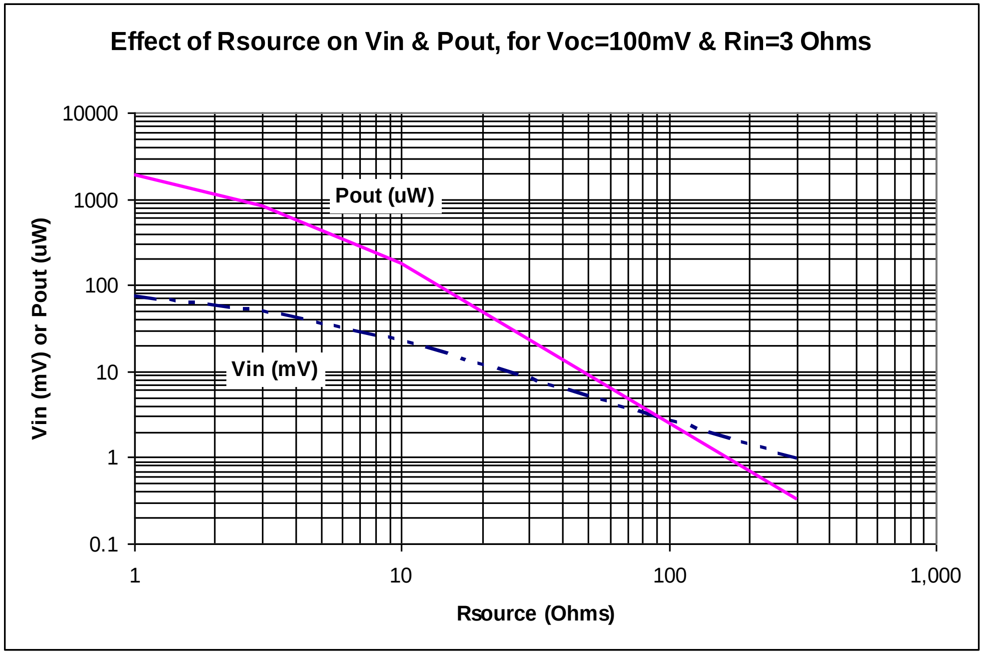




- To extract the most power possible from a source, the load resistance much match the source
- For a 3Ω source, the most power is extracted if the load is also 3Ω
- ***However*, if the source resistance is reduced to 1Ω, power to a 3Ω load will still be increased**

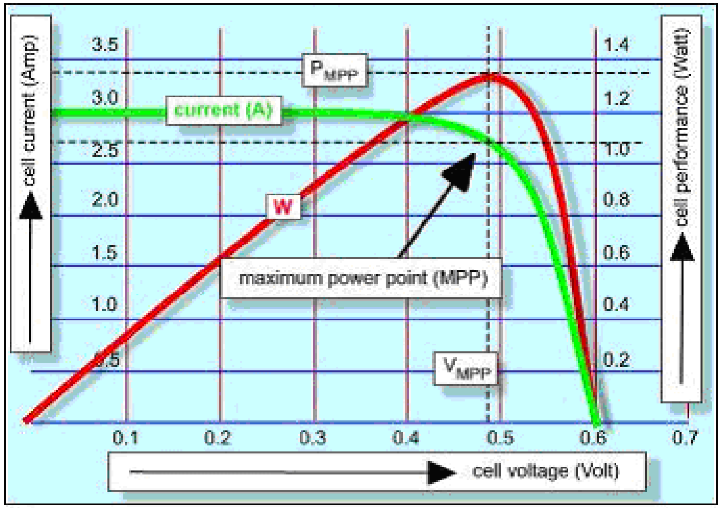
Load Matching to the LTC3108 & LTC3109 TEG Power Converters

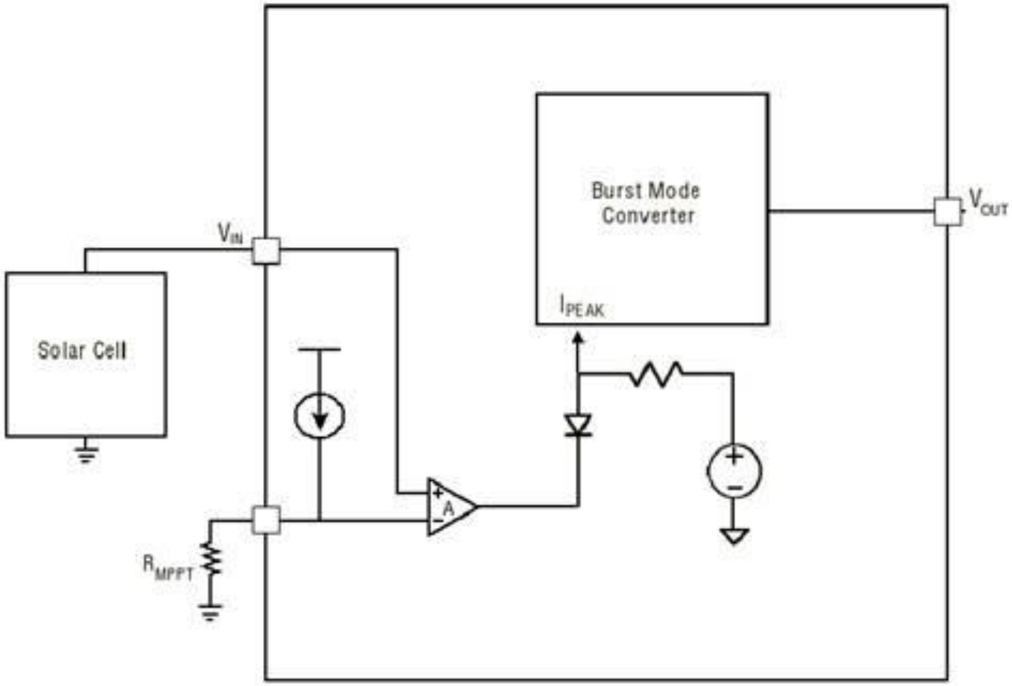




- The Rin of the LTC3108 and LTC3109 converters is in the range of 2.5 – 5Ω (varies with Vin & xfmr ratio)
- Traditional TEGs, with a resistance of 0.5 – 3Ω, provide a good match to the converter
- Sources with high resistance are better suited to a true MPPC (Maximum Power Point Control product)

Q: What is MPP and how can a power converter implement it?





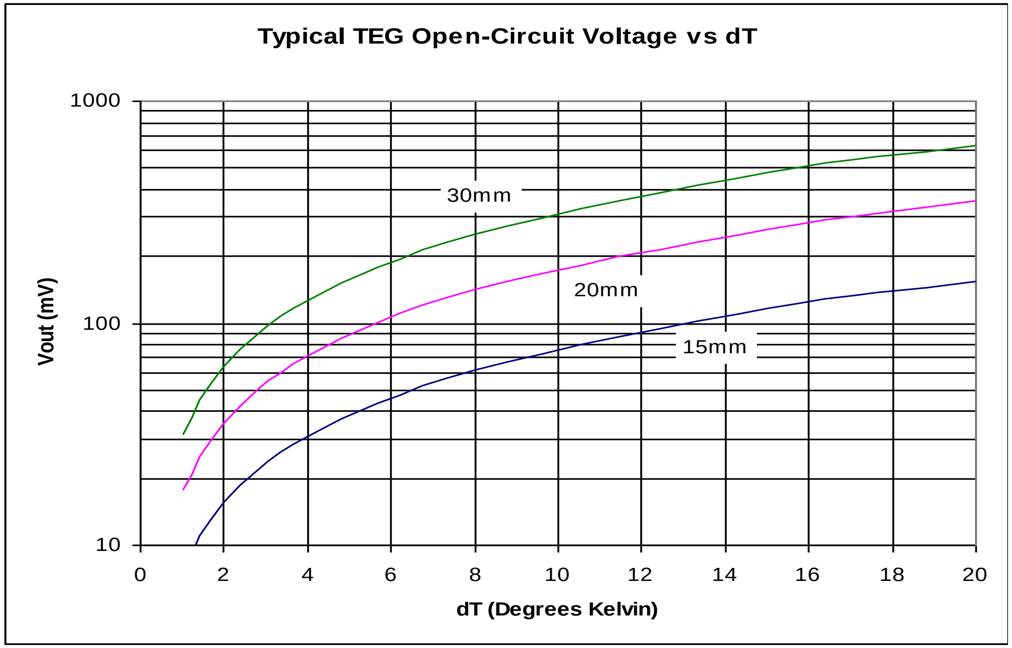
A: MPP is the Photovoltaic (PV) cell equivalent of load matching. For most PV cells, the MPP voltage is ~70 to 80% of the open circuit voltage (Voc). Load matching is achieved by regulating the INPUT voltage of the power converter (output of PV cell) equal to the Maximum Power Point (MPP) voltage of the PV cell.

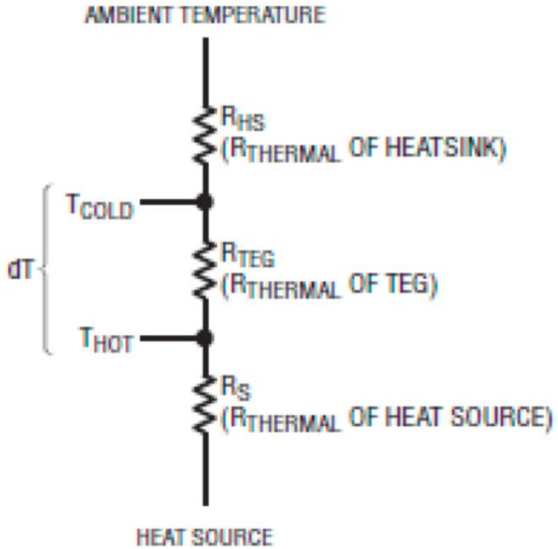
Step 3: Converting Harvested Energy into a Regulated Output

If Thermal Source:

1. Characterize Thermal environment – how Hot or Cold is the surface where the TEG will be attached and what is the Ambient temperature?
2. Select the appropriate TEG/heatsink combination to maximize the thermal gradient.
3. Can the Thermal energy source be either above or below ambient temperature?
4. Select the appropriate Power conversion IC or circuit to provide the regulated voltage output and stored energy management.

Typical TEG Selection Criteria





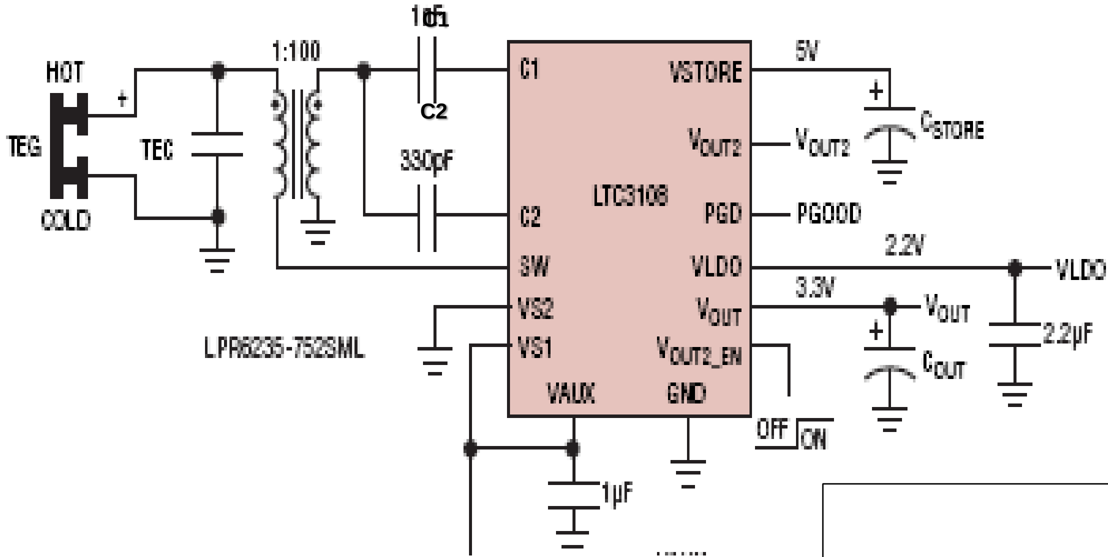
$$dT = (T_{SOURCE} - T_{AMBIENT}) \bullet \frac{R_{TEG}}{R_S + R_{TEG} + R_{HS}}$$

Rules of Thumb in Selecting a TEG:

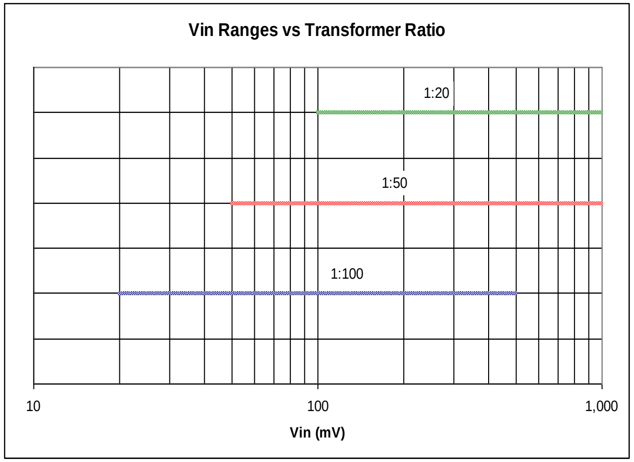
- **Choose the TEG with the highest (Vmax*Imax) product for a given size**
- **Open-circuit TEG Vout ≈ #couples ● 250µV ● ΔT**

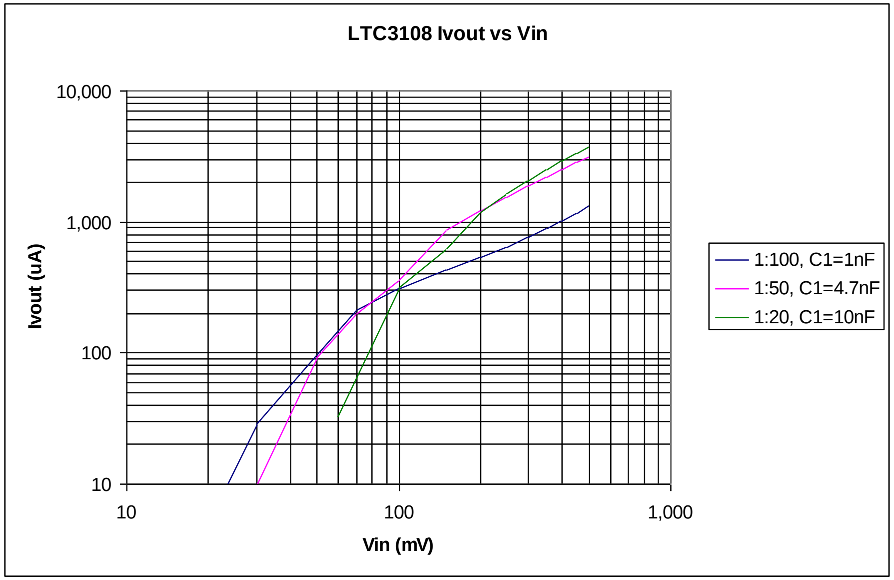
  (example: V_{OC} of a TEG with 127 couples @ 4ºKΔT = 127mV)
- **Heatsink is required to maximize dT across the TEG**

Choose a Power Conversion Solution: LTC3108 example



- o Typical startup voltage of ~20mV
- o Choose transformer ratio based on Vin
- o Min Vin < 50mV, use 1:100 ratio
- o Min Vin > 50mV, use 1:50 ratio
- o Min Vin > 200mV, use 1:20 ratio
- o The LTC3108-1 offers different fixed Vout options





LTC3108 Block Diagram Review

Rectifier

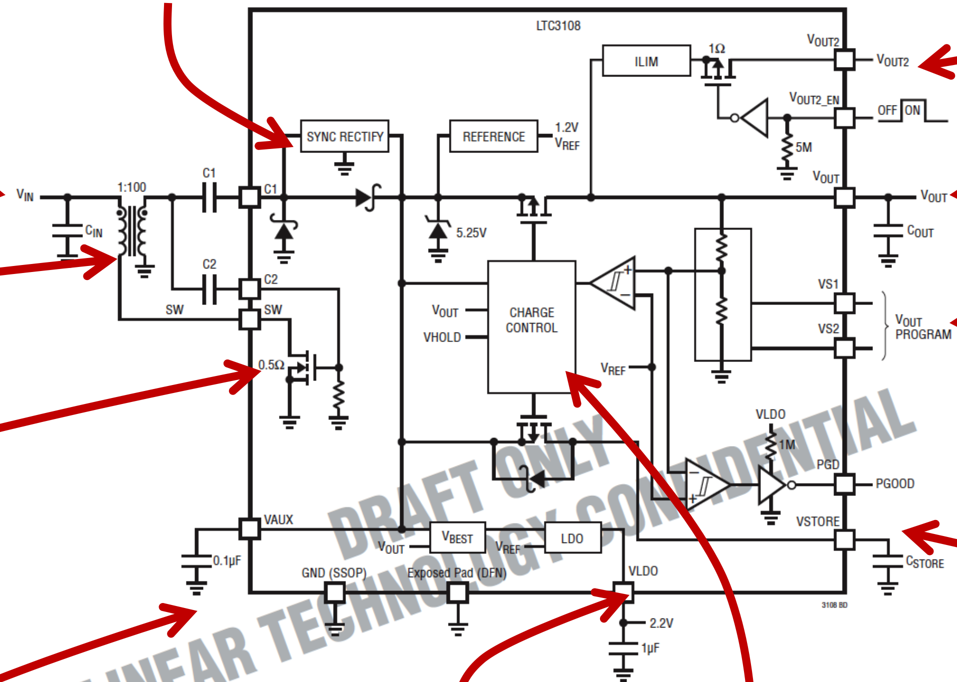
VOUT2: Switched VOUT

20mV Vin Source

VOUT: Main Output

Digital Vout Select

Compact Step-Up
transformer



Depletion Mode

MOSFET

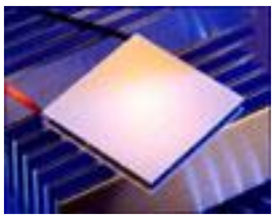
VSTORE: Energy
Reservoir

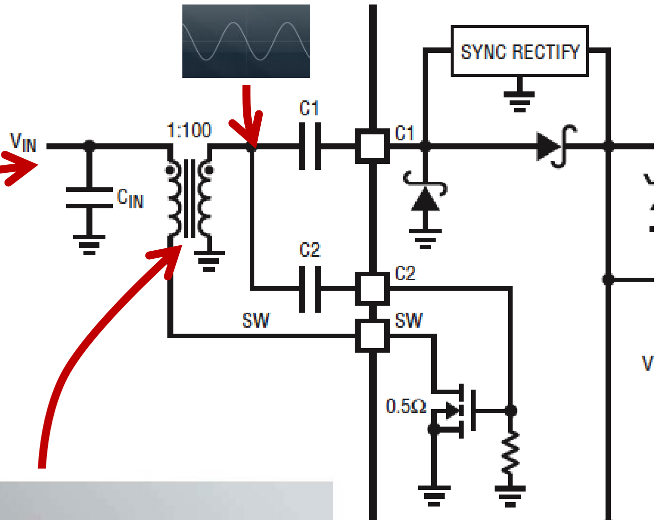
3mA LDO:
uController
power

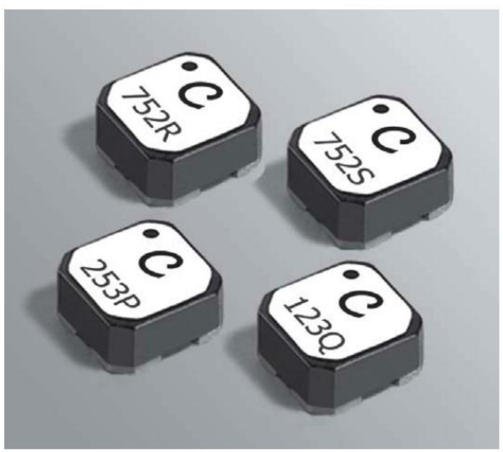
Charge Control and Prioritizer

VAUX: Intermediate
Charge storage and
IC bias supply

LTC3108 Feature: 20mV Resonant Boost Topology



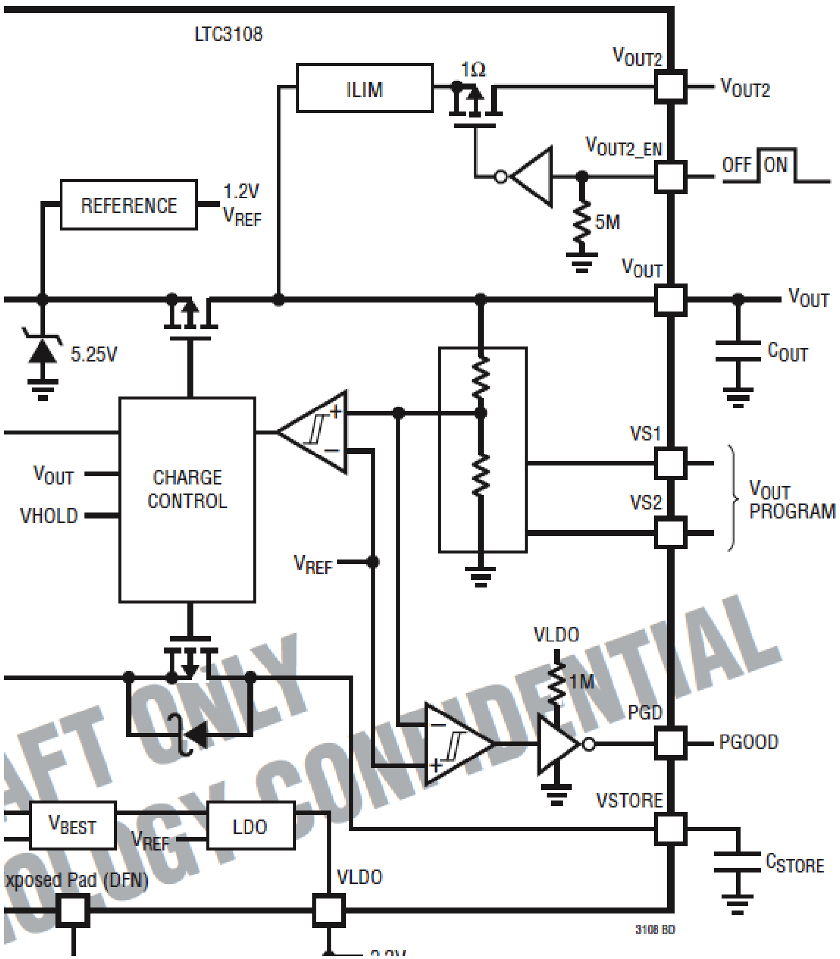




Part number[1]	Primary (L1) inductance[2] ± 20% (μH)	Turns ratio	DCR max (Ohms) L1	DCR max (Ohms) L2	SRF typ[3] (MHz)	Isat[4] (A)
LPR6235-752RML_	7.5	1 : 90	0.085	267	257	1.6
LPR6235-752SML_	7.5	1 : 100	0.085	305	244	1.6
LPR6235-123QML_	12.5	1 : 50	0.080	200	382	0.9
LPR6235-253PML_	25	1 : 20	0.20	58	580	0.7

- 20mV Operation or **~1deg dT** if powered from a Peltier Effect Thermal Electric Generator (TEG or TEC)
- LTC proprietary compound Depletion mode N-Channel MOSFET makes extreme low voltage possible
- Circuit Self-oscillates, resonant circuit formed by Lmag and Cg
- Built-in Synchronous rectification improves Energy harvesting “yield”
- Optimized transformers for the LTC3108 are standard Coilcraft parts, 6mm x 6mm x 3.5mm

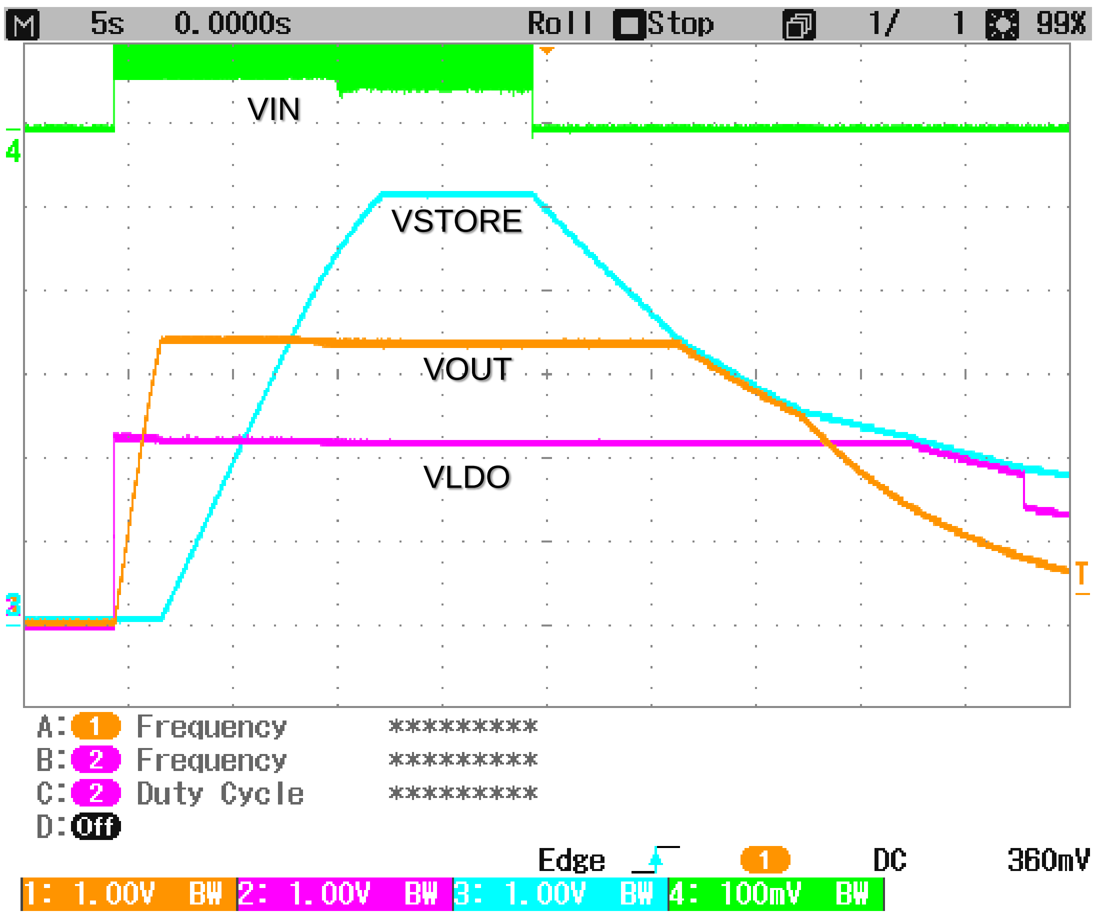
LTC3108 Feature: Harvested Energy Management



- Harvested Energy is preferentially sent to VOUT
- Excess harvested energy is sent to VSTORE
- VSTORE will backfeed VOUT in the event of a power outage
- VOUT2 is a switched ON-OFF version of VOUT for Sensors that don't have a SD input
- Charge Control block provides all of the intelligence to ensure seamless operation

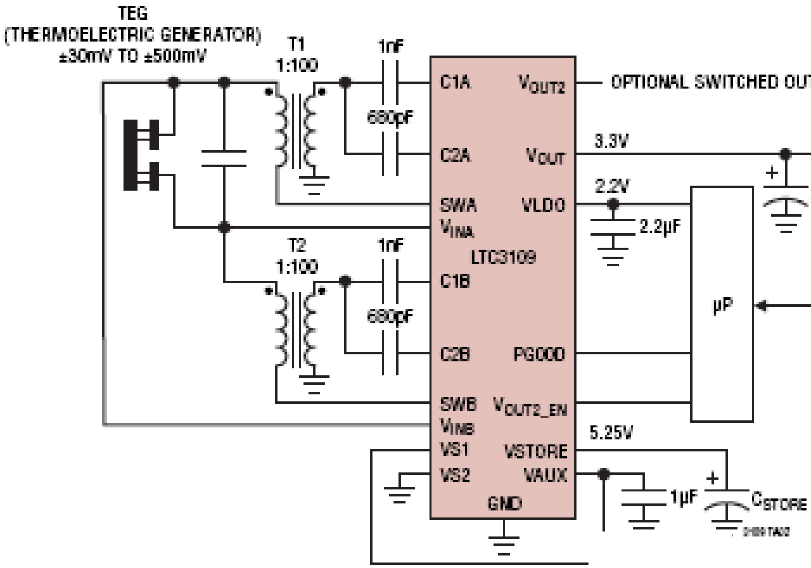
LTC3108 Voltage Sequencing and Charge Management

Power Up Power Down

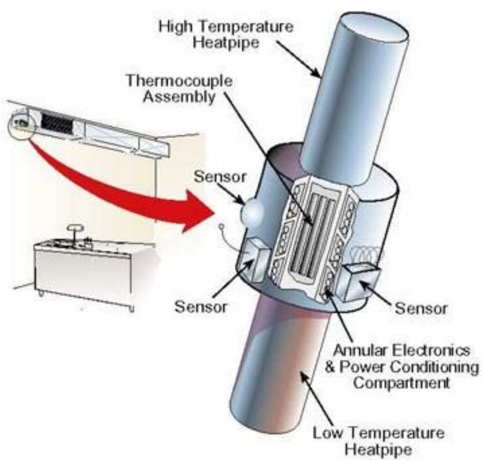


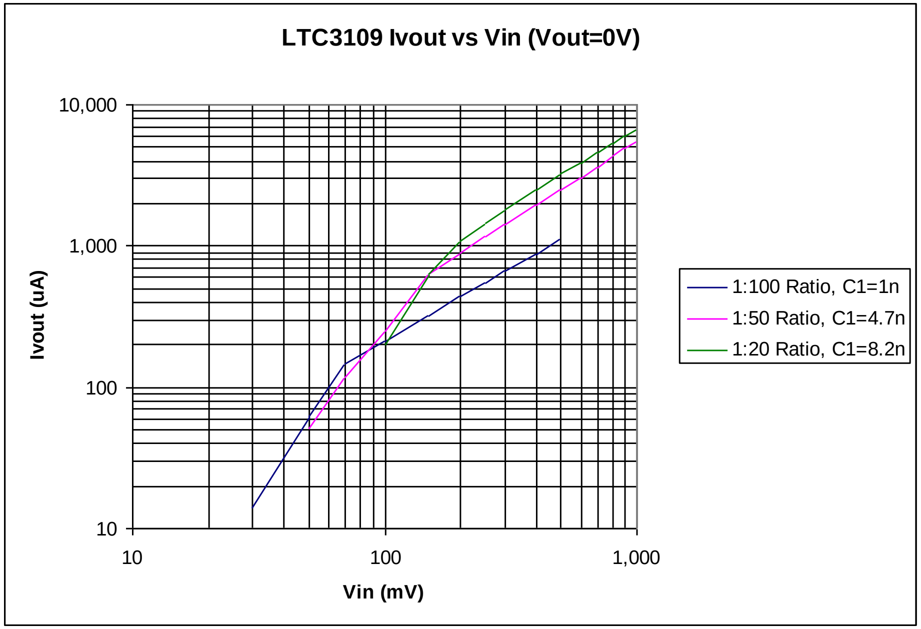
- VLDO: 2.2V fixed
- VOUT: 2.35V, 3.3V, 4.1V or 5V (LTC3108 & LTC3109)
- VOUT: 2.5V, 3.0V, 3.7V, 4.5V (LTC3108-1)
- VSTORE charges up to 5.25V

Hot and Cold Thermal Source: LTC3109 Auto-Polarity Example

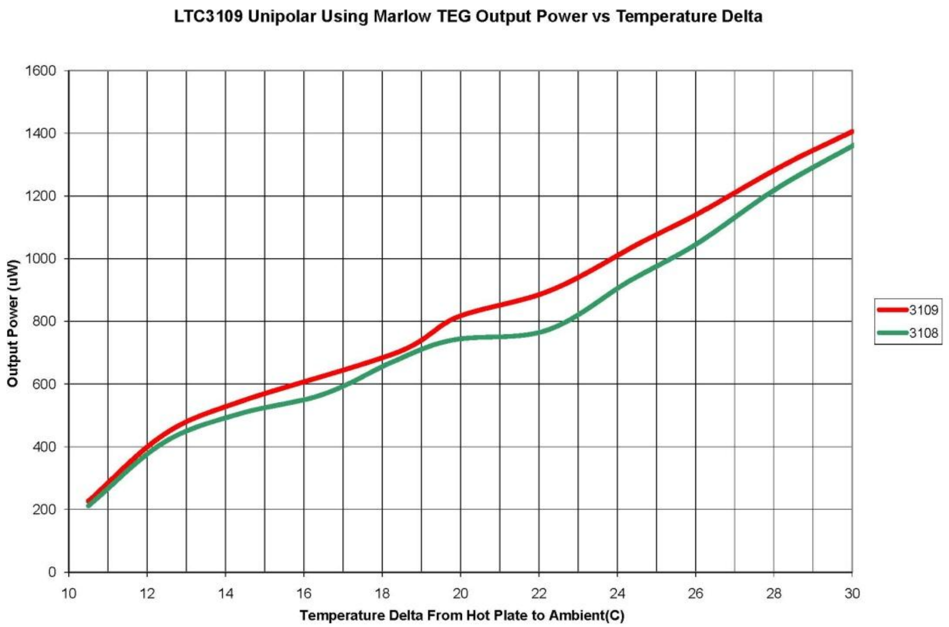


- o Typical startup voltage of ±30mV
- o Operates equally well from either polarity
- o Can operate from a low frequency AC input
- o Uses two identical transformers
- o Patent Pending architecture





LTC3108 & LTC3109 Unipolarity Output

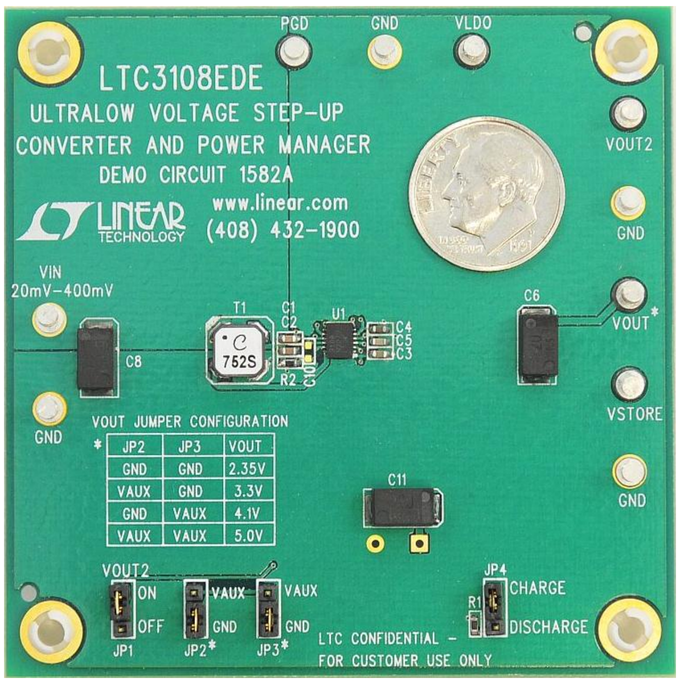


Temperature is ambient to source

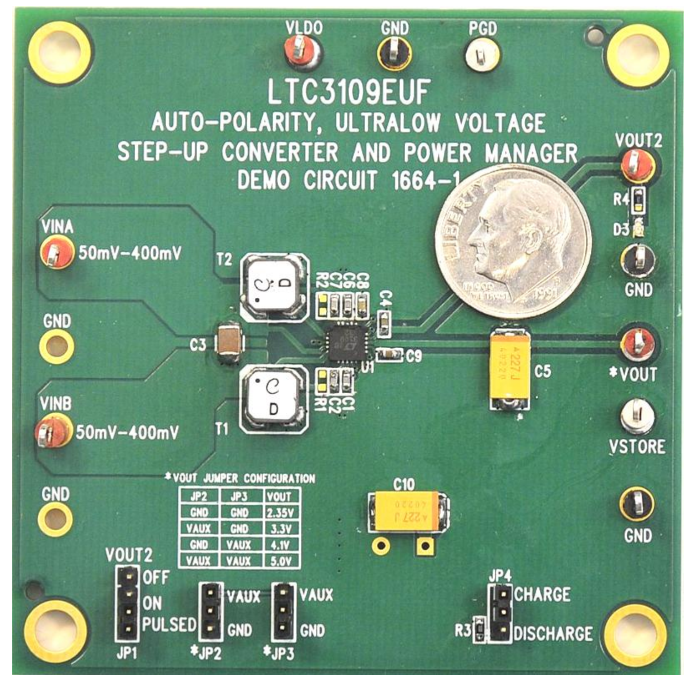
LTC3108 & LTC3109

- Ultra-Low Voltage Thermal Energy Harvesters
- Use a resonant step-up architecture
- Optimized for low resistance sources (0 – 5Ω)

Uni-polar: Vin > 20mV



Autopolarity: Vin > ±30mV
(or Uni-polar: Vin>15mV)

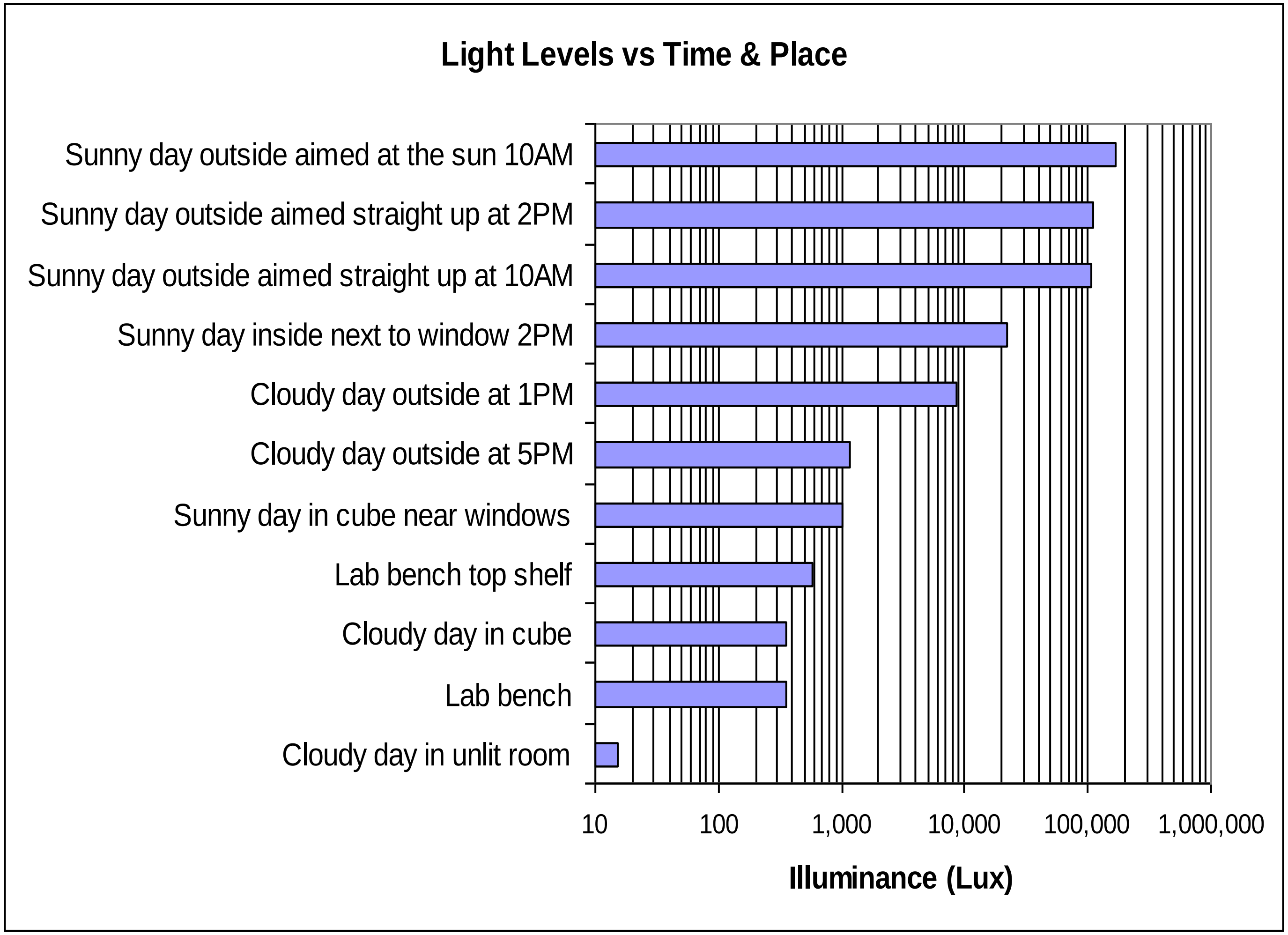


Step 3 (continued): Converting Harvested Energy into a Regulated Output

Photo Voltaic Source:

1. Characterize Ambient light environment – what is the average light intensity (Lux), constant or intermittent?
2. Depending on average power requirements and (1), select a PV cell or cells.
3. If the Ambient light source is intermittent, decide on what type of energy storage to use: rechargeable or primary battery, capacitor…
4. Select the appropriate Power conversion IC or circuit to provide the regulated voltage output and stored energy management.

Typical Ambient Light Intensity Levels



~3 orders of magnitude between Outdoor and Indoor light!

Photovoltaic Cell Characteristics

Monocrystalline Cells (Si-based):

- High PV conversion efficiency
- Generally more expensive than other options
- Low output voltage (0.5V typical)
- Sensitive to sunlight more than indoor lights

Polycrystalline Cells (Si-based):

- Generally cheaper than monocrystalline
- Low output voltage (0.5V)
- High PV conversion efficiency
- Sharper power drop off at low light intensities than monocrystalline
- Like monocrystalline, more sensitive to sunlight than indoor light sources

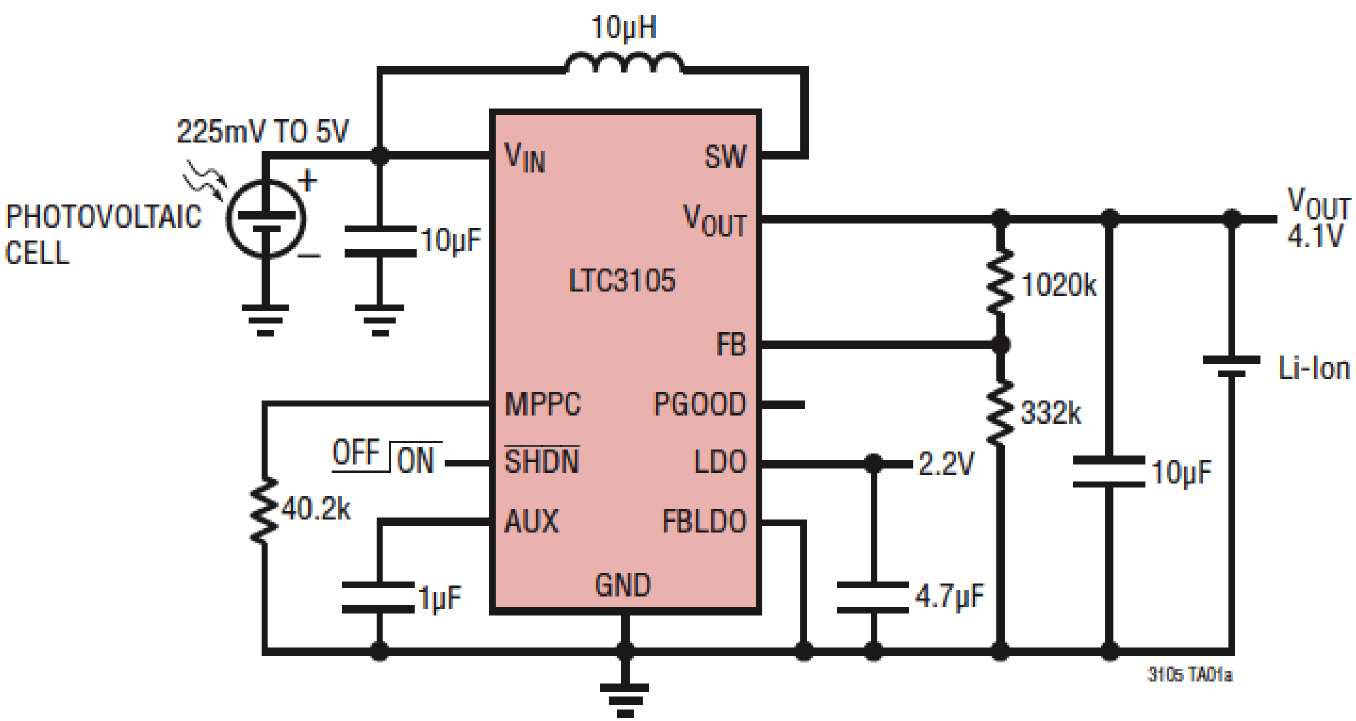
Thin Film, Dye Sensitized:

- Lower PV conversion efficiency
- Many different types of thin films
- Generally Higher output voltages (2V to 5V)
- Can be made in more shapes, fabricated on glass or metal substrate
- Higher sensitivity to fluorescent light than crystalline cells
- Can provide higher overall efficiency due to higher conversion efficiency (2V->3.3V instead of 0.4V->3.3V)

Select the Power converter solution: LTC3105 Example

- Synchronous Boost Converter + LDO starts up at 250mV
- ***Includes Maximum Power Point Control (MPPC)***, which adjusts the peak inductor current to maintain Vin at a programmed voltage
- Operates from higher resistance sources than traditional boosts
- Uses burst-mode architecture with variable Ipk and Ivalley

Single Photovoltaic Cell Li-Ion Trickle Charger



LTC3105: Block Diagram Review

Low Voltage Startup

250mV (typ)

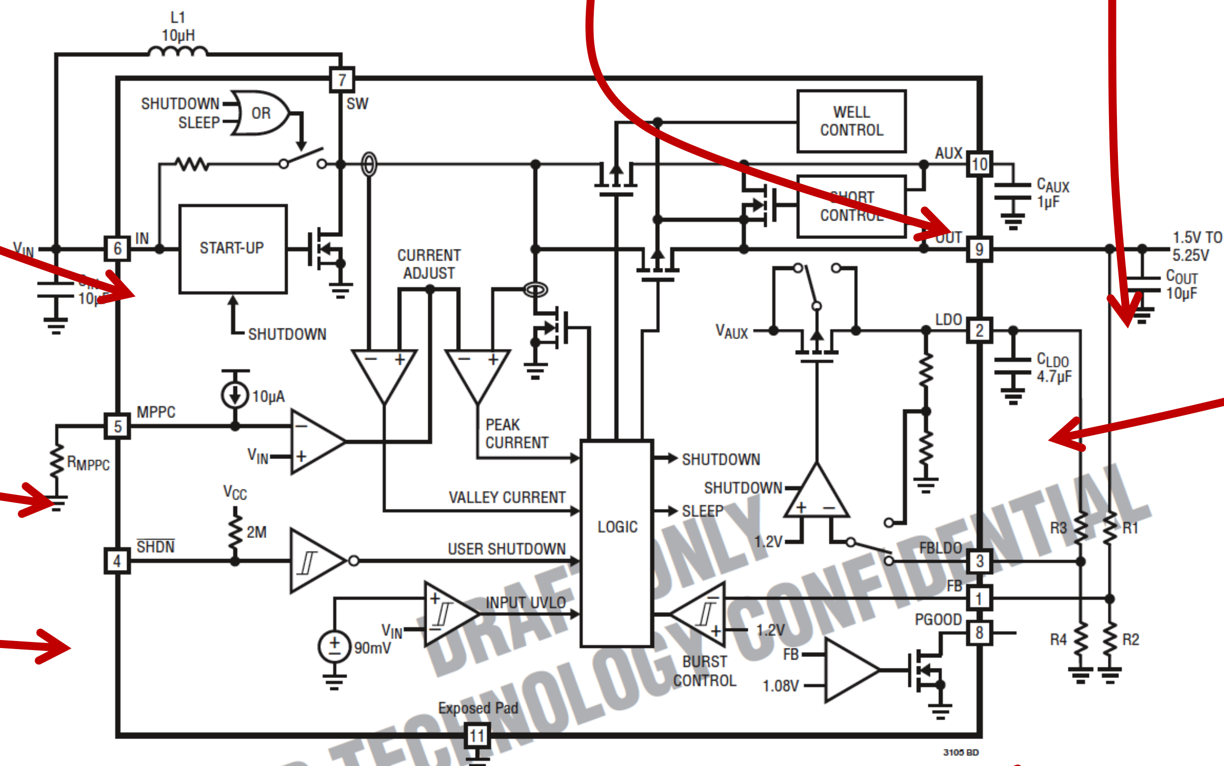
VAUX

Main VOUT

LDO Output

MPPC Setpoint

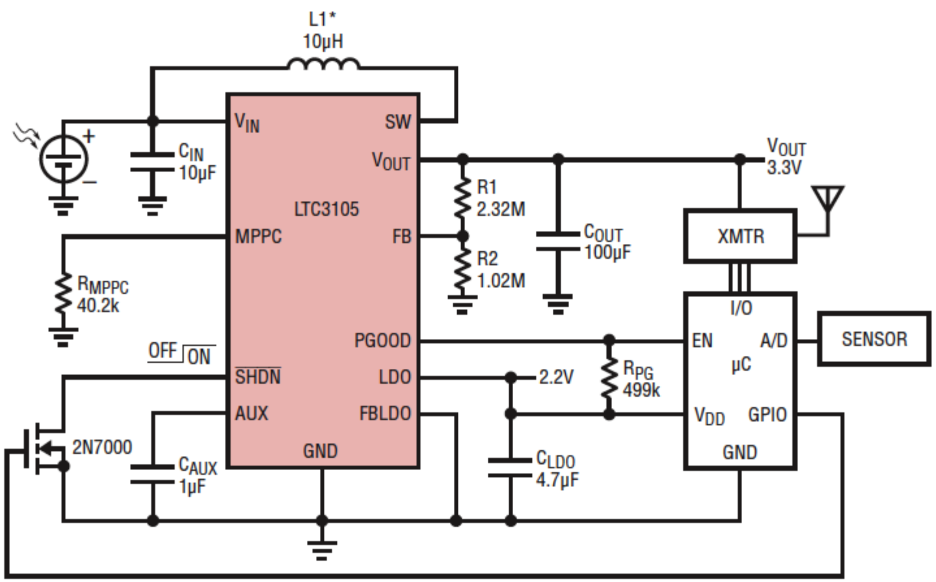
ON-OFF



Power Good

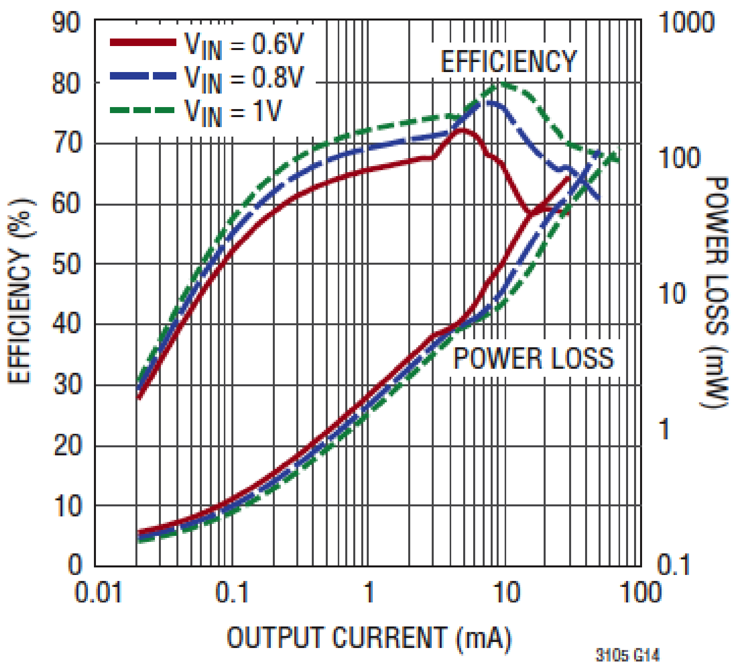
LTC3105 Typical Characteristics for WSN Application

Single-Cell Powered Remote Wireless Sensor

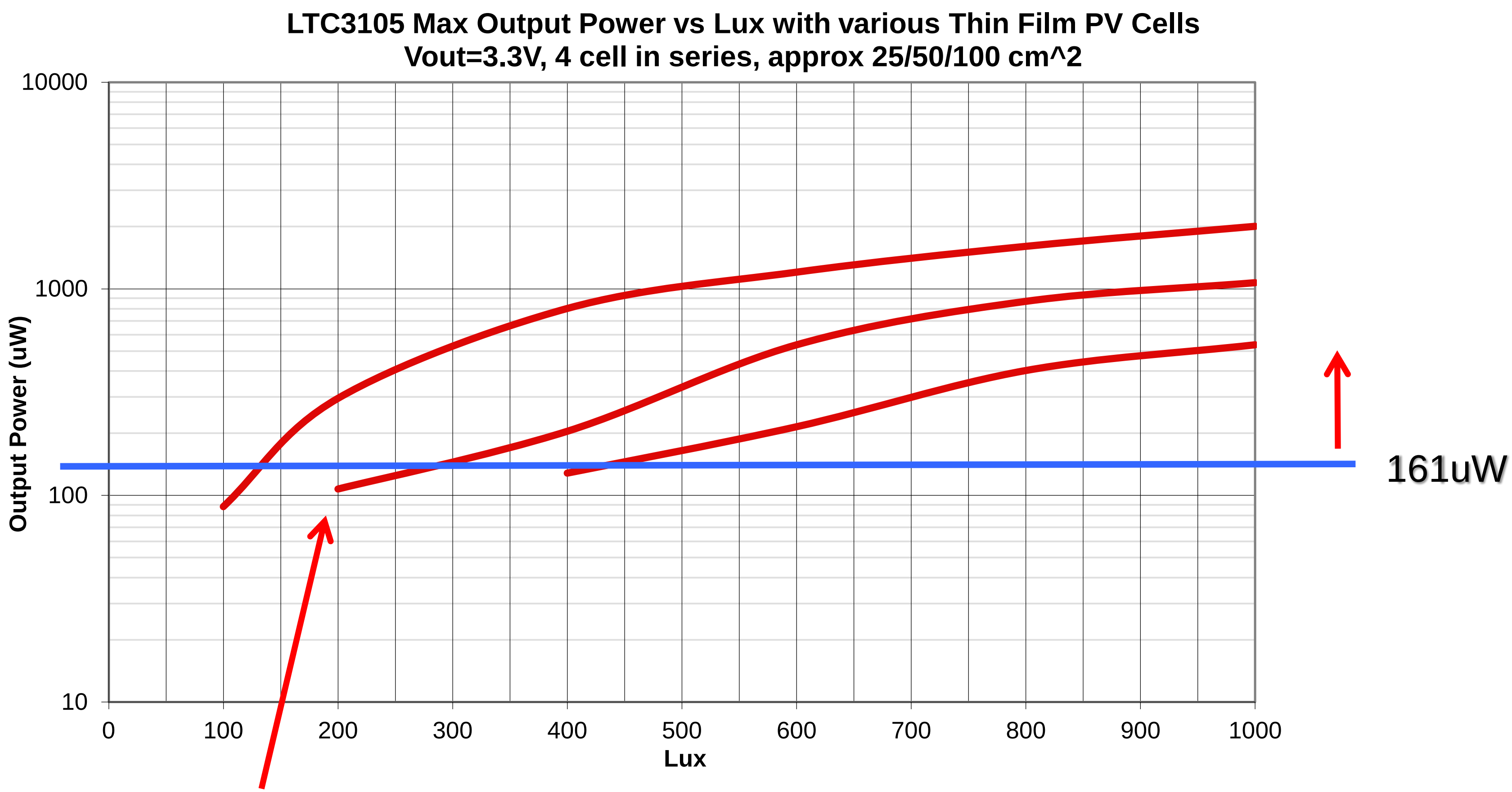


* COILCRAFT MSS5131-103MX

Efficiency vs Output Current and Power Loss, V_{OUT} = 3.3V



LTC3105 Output Power at Indoor Light Levels



Only ~200 Lux required to meet example application limits with some cells

LTC3105 Maximum Power Point Control simplified

Simple Single Resistor Programming

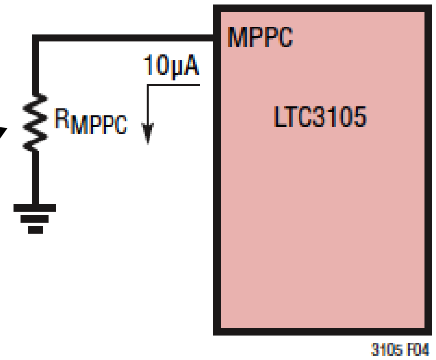


Figure 4. MPPC Configuration

- Maximum Power Point Control circuit Servo's Vin to equal V(MPPC)
- V(MPPC) = 10uA x R(MPPC)
- Set V(MPPC) = ~ 75% of Voc for Solar Cell and 50% of Voc for TEG source

Inexpensive Diode provides Temperature compensation

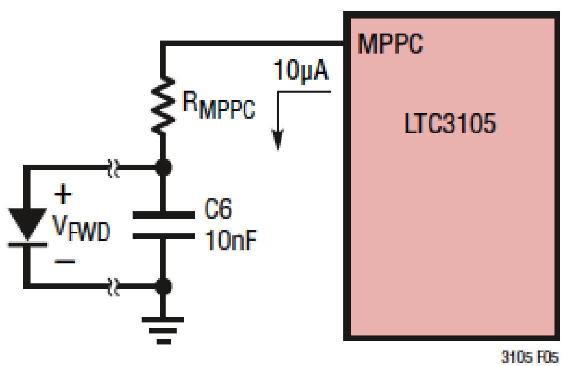
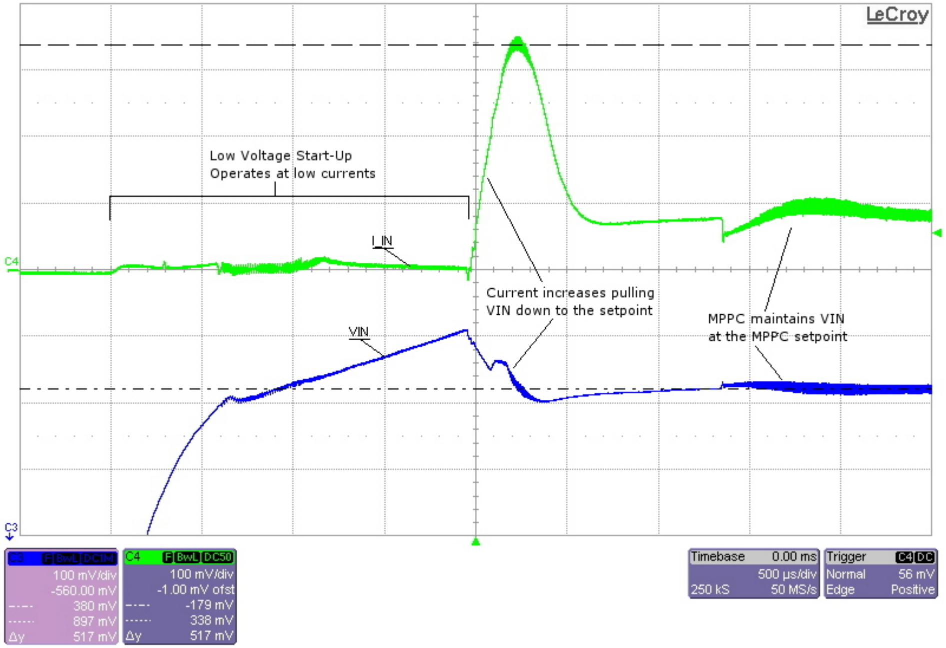


Figure 5. MPPC Configuration with Temperature Adjustment

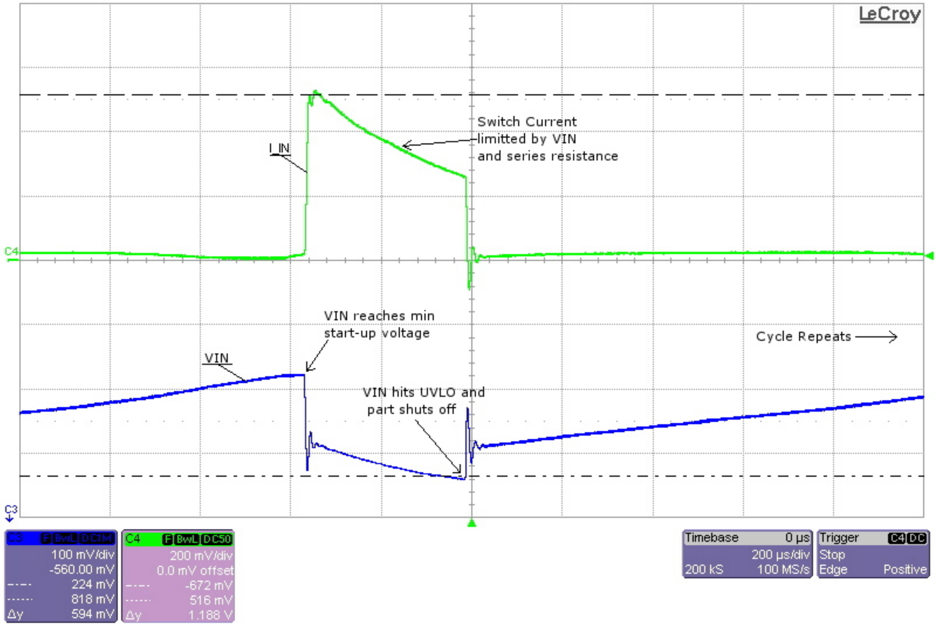
LTC3105 Maximum Power Point Control Startup Example

LTC3105 with MPPC



✓ **Solar Cell is regulated to Max Power Point**

Comparable Boost Converter without MPPC



✘ **Solar Cell is Overloaded and circuit will not start**

LTC3105: Can be used with other Power Sources

Industrial Current Loop
Power scavenger

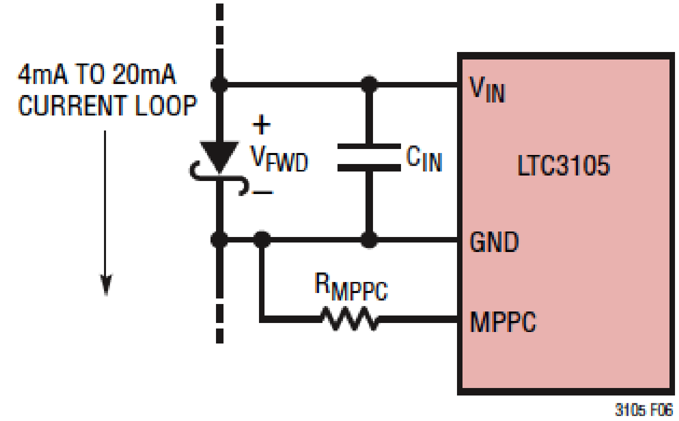
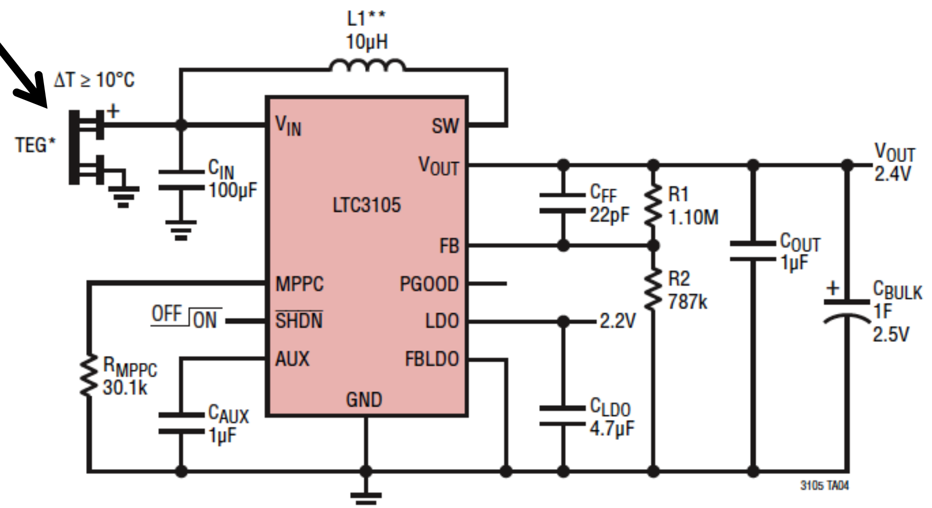


Figure 6. Current Loop Power Tap

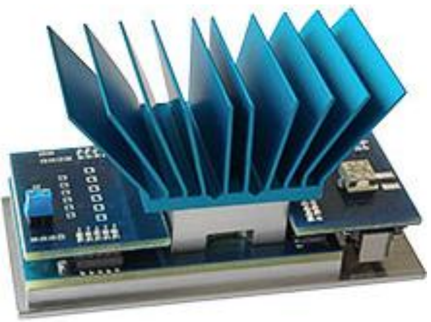
High Output Voltage,
Micro-Scale TEG
(MicroPelt)

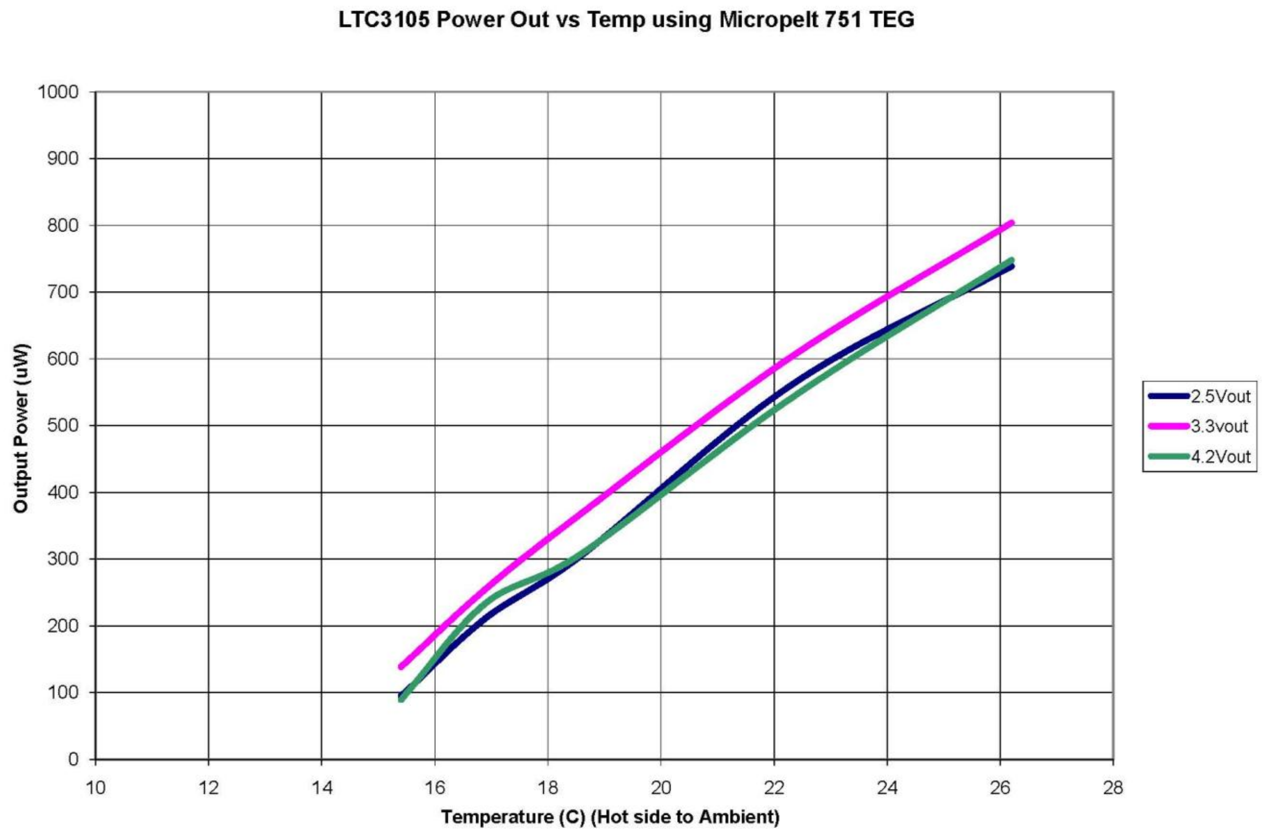
Thermoelectric Generator to 2.4V Super Capacitor Charger



* MICROPELT MPG-D751
** COILCRAFT MSS5131-103MX

LTC3105 with Micropelt TEG



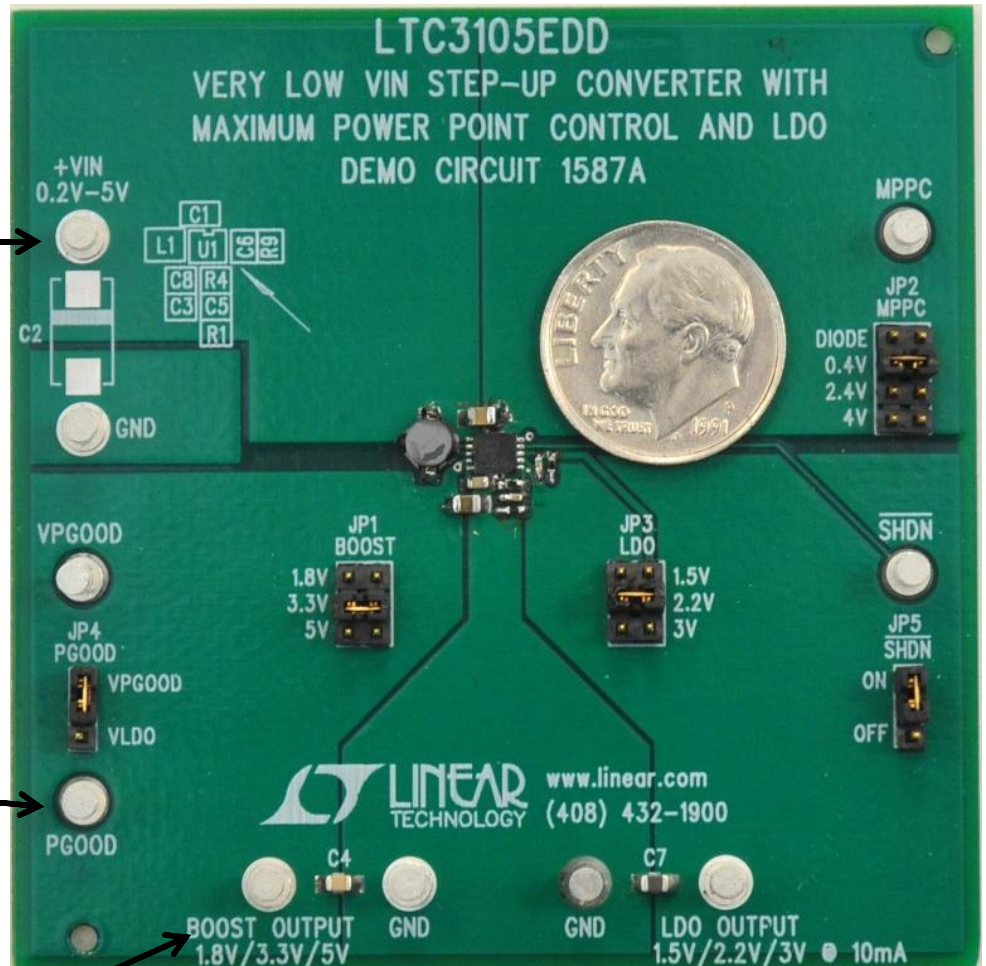


LTC3105 can operate with high source resistance TEGs

Temp delta ambient to hot side, actual TEG delta 7-8 degrees

LTC3105 Energy Harvester

Power Source IN



Main VOUT GOOD Flag

Main VOUT

Auxiliary LDO VOUT

LINEAR TECHNOLOGY

Advantages of Integrated Power Management Solutions

- ✓ Single IC replaces up 35 discrete components, multiple functions
- ✓ Predictable and reliable operation in harsh Industrial environments
- ✓ Integrated MOSFETs optimized for speed and ultra-low Iq
- ✓ Multi-MegOhm Resistors integrated, no manufacturability concerns
- ✓ Off the shelf Integrated Solutions for all types of practical transducers
- ✓ Compatible with all types of storage elements

…this is very hard to do with discrete components!

LINEAR TECHNOLOGY

Summary - Energy Harvesting Trends

- Energy Harvesting applications are potentially everywhere
- Power needs of typical applications continue to drop
- Transducers are improving – better optimized for EH applications
- Tools emerging to help characterize ambient energy sources
- Transducer datasheets providing more relevant design information
- Regulated power can be reliably obtained with properly designed charge management system

- New energy harvesting ICs provide optimized solutions:

LTC3108/9	Thermal
LTC3105	Low Voltage Solar
LTC3588	Vibration / Piezo
LTC4070/1	Nanopower Battery Chargers

Thank You

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