Practical Design Considerations for Piezoelectric Energy Harvesting Applications

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

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Agenda

- Energy Harvesting Basics
  - What are the benefits? Where is it useful?
  - Design Example: Vibration Powered Wireless Sensor Node
- Selecting the Right Transducer
  - Piezogenerator models, capabilities, limitations
- Converting Harvested Energy into a Regulated Output
  - Rectification, start-up, efficiency, and over-voltage concerns
- Integrated Solutions

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Energy Harvesting – where is it useful…?

- Where line power is unavailable or costly
- Where batteries are difficult or costly to replace
- Where energy needed only when ambient energy present

Asset Tracking/Monitoring

Building Security, Lighting & Climate Control

Plant Automation

Remote Monitoring

Typical Application: Remote Wireless Sensors

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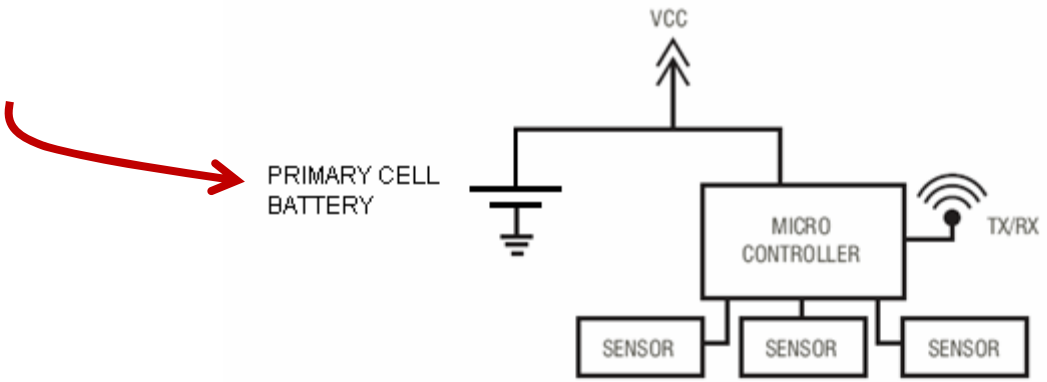
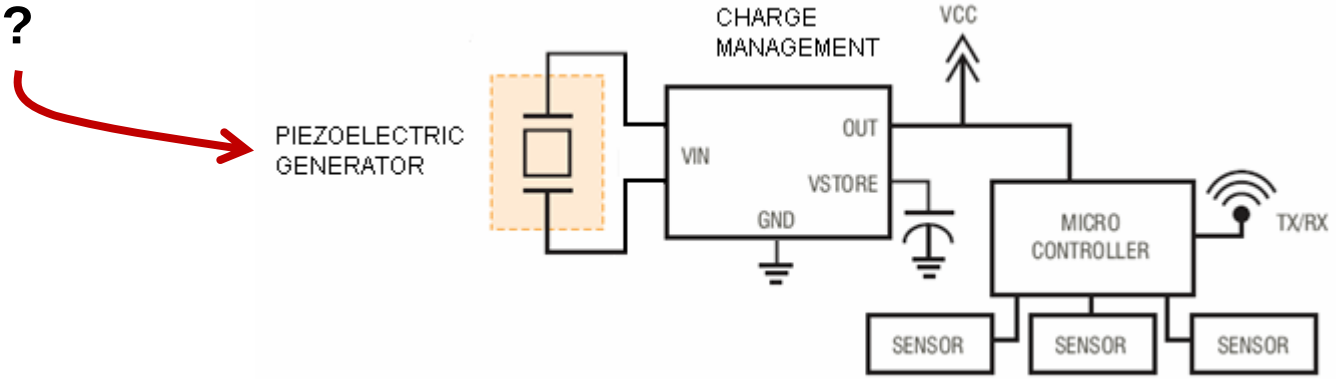
Design Example:
Vibration (Piezo) Powered Wireless Sensor Node

How can I replace this…



…with this?



Motivation: Eliminate need to replace dead batteries

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Good News: Sensor Energy/Power Requirements are LOW

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 10 seconds requires **48.2uW** (482uJ / 10s)

Wireless sensor power requirements continue to drop

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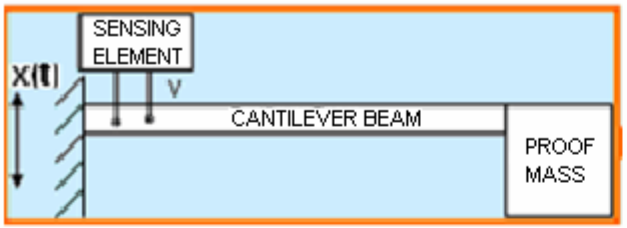
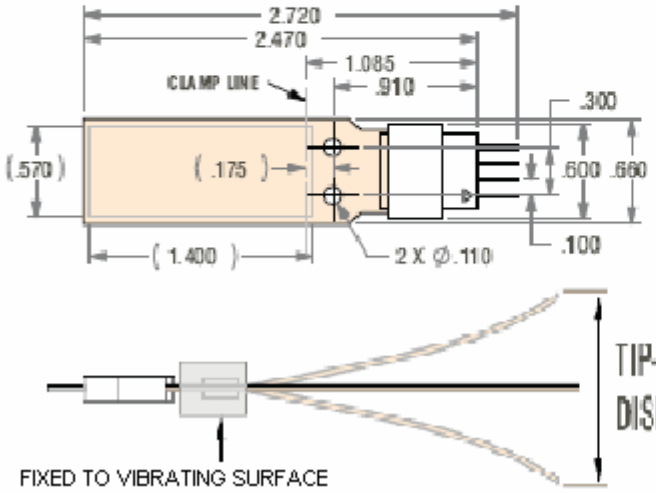
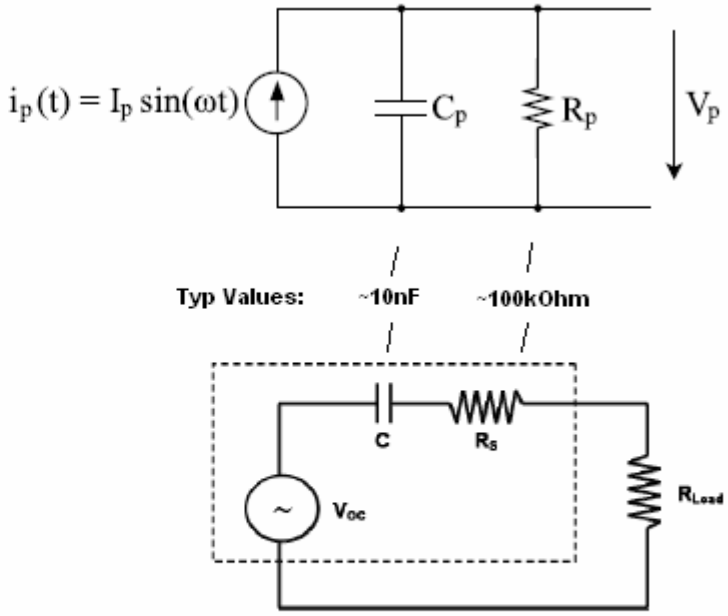
Selecting the Proper Transducer – Piezogenerator Basics







Piezogenerator Electrical Models

- Vibrating piezos generate an A/C output
- Electrical output depends on frequency and acceleration
- Open circuit voltages may be quite high at high g-levels
- Output impedances also quite high

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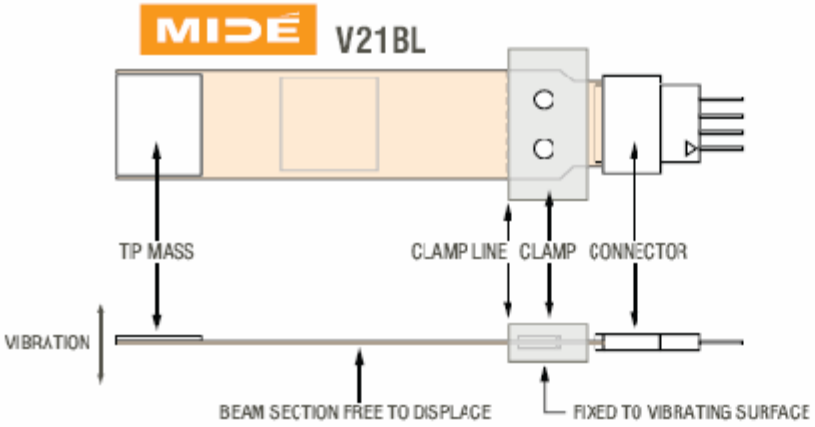
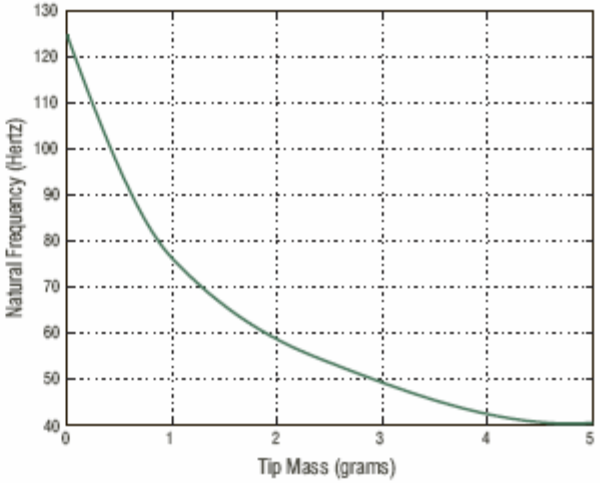
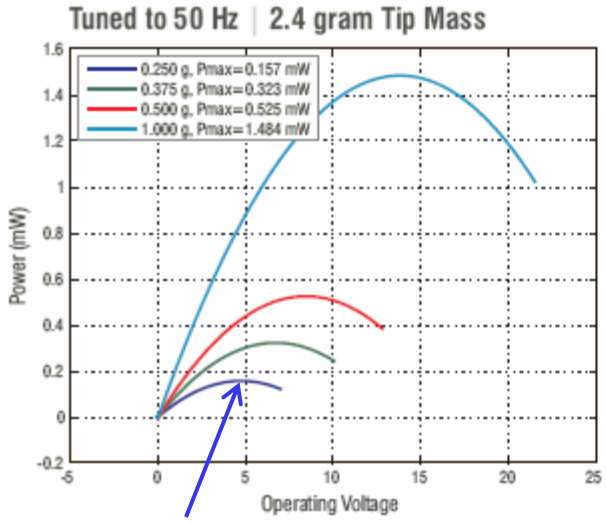
Q: How much power can piezo transducers generate?







Tip Mass (gram)	Fn (Hz)	Amplitude (g)	Open Circuit Voltage*
0	110	0.25	3.95
0	110	0.375	5.35
0	110	0.5	6.6
0	110	1	12.1
1	65	0.25	8
1	65	0.375	9.9
1	65	0.5	12.4
1	65	1	22.1
2.4	50	0.25	9.8
2.4	50	0.375	13.7
2.4	50	0.5	19.1
2.4	50	1	27.5
4.8	40	0.25	13.2
4.8	40	0.375	19.2
4.8	40	0.5	25.9
4.8	40	1	44.4

Rectified P_{OUT} vs. Vibration
>100uW to >1mW POUT at F_{RES}

VOC goes up at high g-levels…
Peak power obtained at ~ VOC/2

A: Plenty…if properly matched to the vibration source

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The Importance of Resonance

Frequency response must match
or power falls off quickly

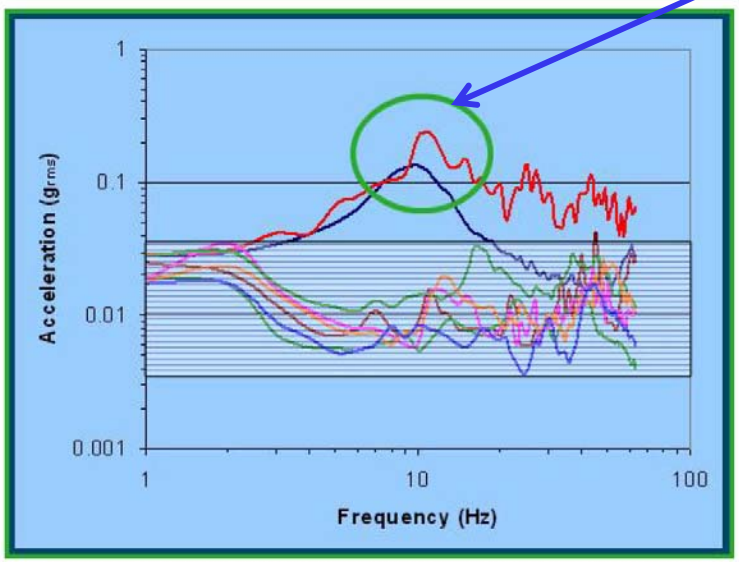
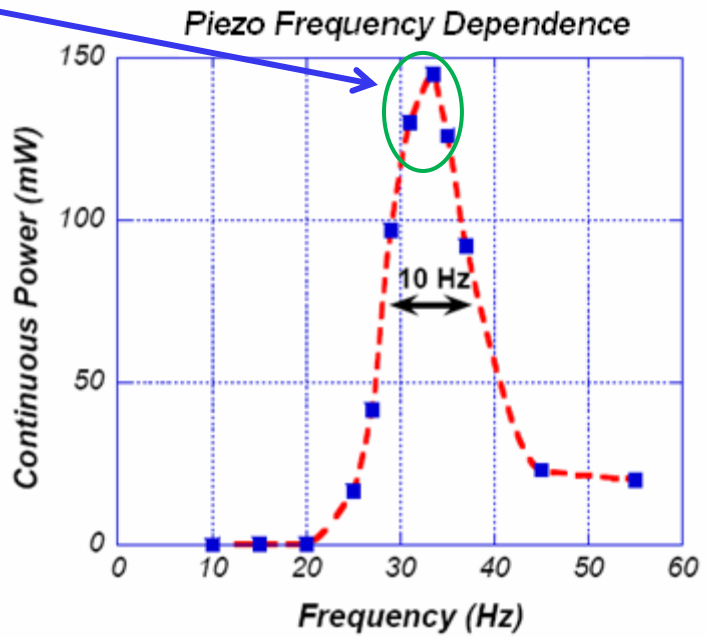


Figure 3. Interior and exterior vehicle vibration data on automobiles, trucks and minivans.

Source: Adaptive Energy Corporation



Source: Advanced Cerametrics Corporation

- Piezogenerators easily tuned for 10Hz - 300Hz resonance
- Provide uW's - mW's with only 0.1g to 2g acceleration

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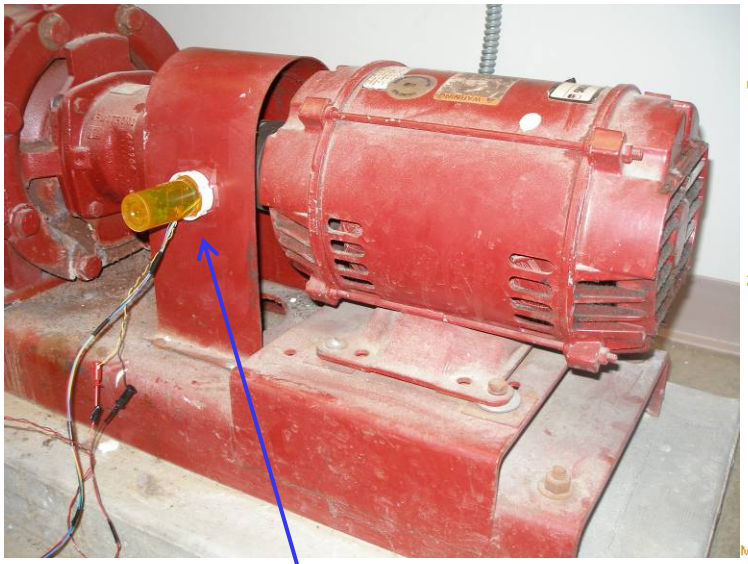
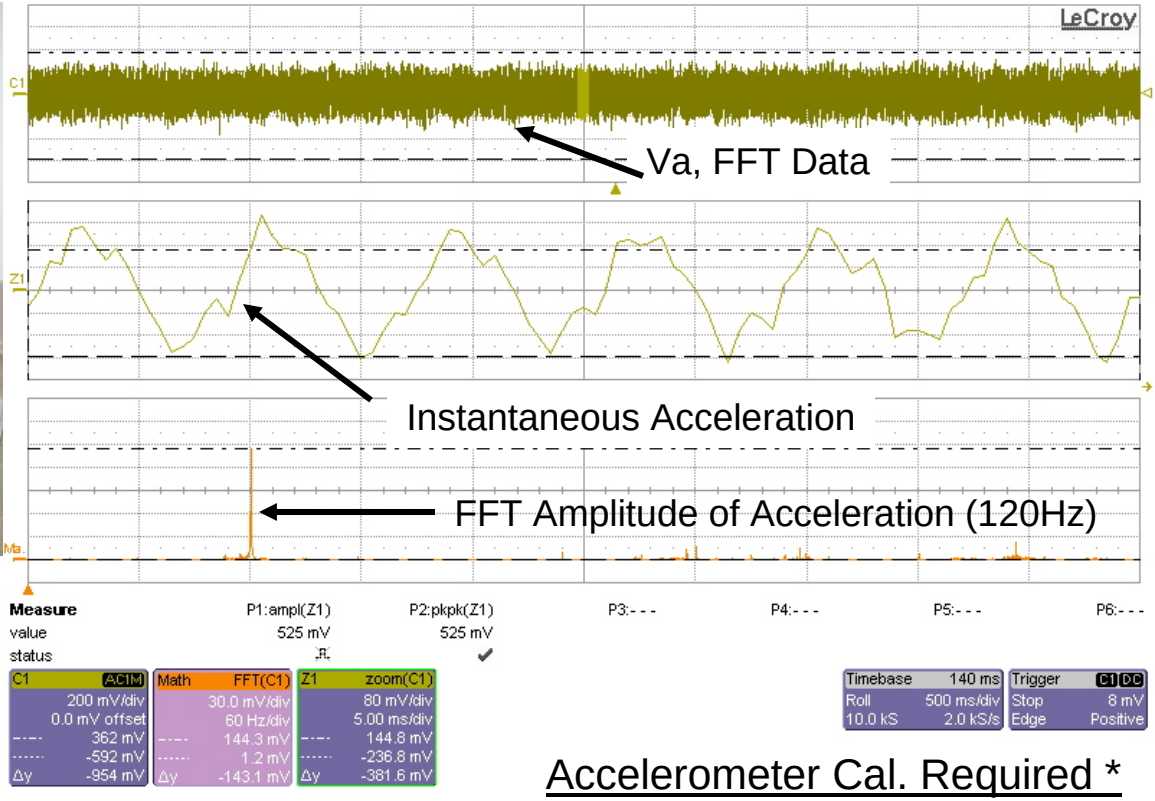
Vibration Sources Need to be Characterized (Do-It-Yourself Method)



3-axis accelerometer…



- Harvester Placed on Motor Shield
- Fs = 120Hz
- Acceleration, a(t) = 0.40*sin(2*p*120*t) [g]

Accelerometer Cal. Required *
(1g DC measurement):

Cap Upwards, x-y = 375mV
Cap Sideways, y-x = 355mV
(143mV / 355mV = 0.40)

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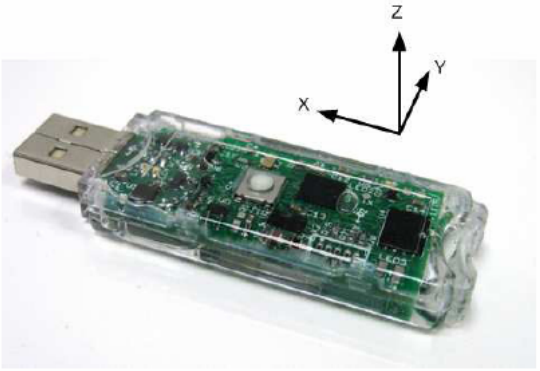
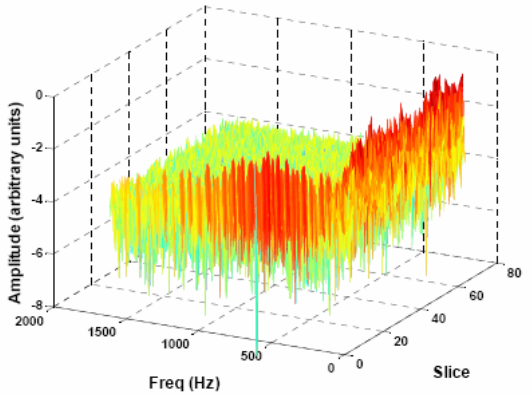
Automated Tools Available

Volture Development Tools

- First step is vibration characterization
  - Frequency content, amplitude, duty cycle
- Mide has developed vibration recorder to meet this need
  - 3-axis
  - 3.2 kHz
  - Simple USB interface
  - Software for extracting valuable information
- Complete System Tools





Source: Mide Corporation

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Piezogenerator selection depends on the following:

- Vibration Source Characteristics

What is the source vibration frequency?

What is the min, typ and max acceleration?

- Application Electrical Characteristics

What is the average power requirement?

What is the operating voltage?

- Application Physical Constraints

How much area available for the piezo element?

What are the environmental conditions (moisture, temperature,…)?

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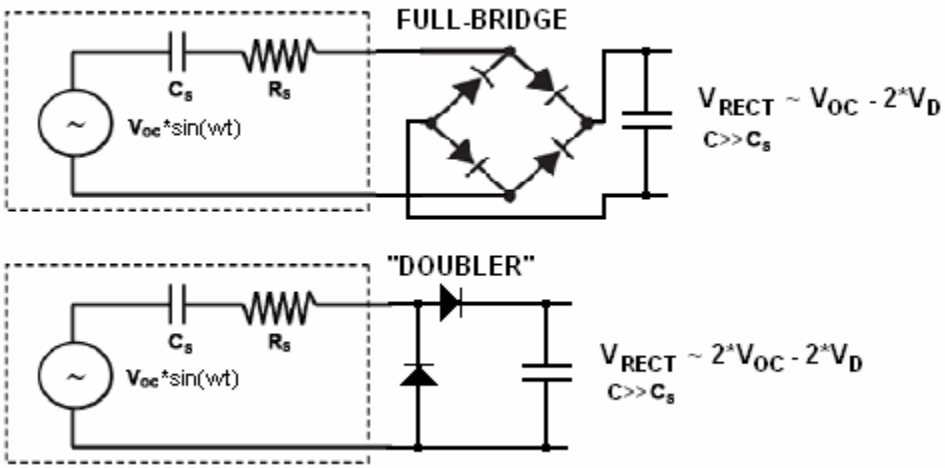
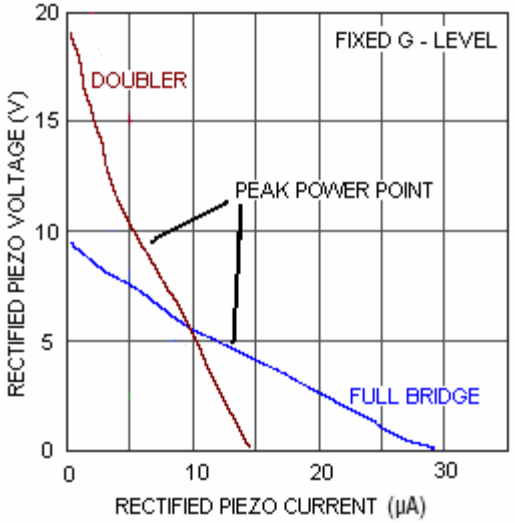
Converting Harvested Energy into a Regulated Output

Step 1: Convert piezo AC output to an unregulated DC (V_{RECT}) supply





Rectification Options:

- Full-bridge
  - Piezo current conducts to the output on both phases
  - Best for high open circuit voltages
- "Doubler"
  - Piezo current conducts to the output on positive phase only
  - Best for low open circuit voltages

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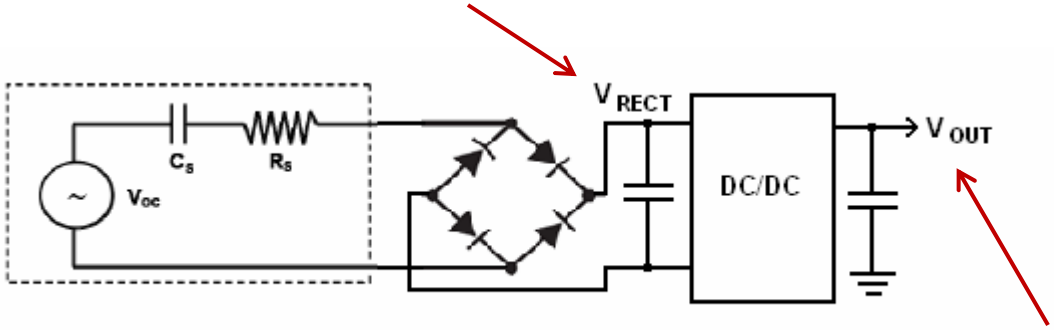
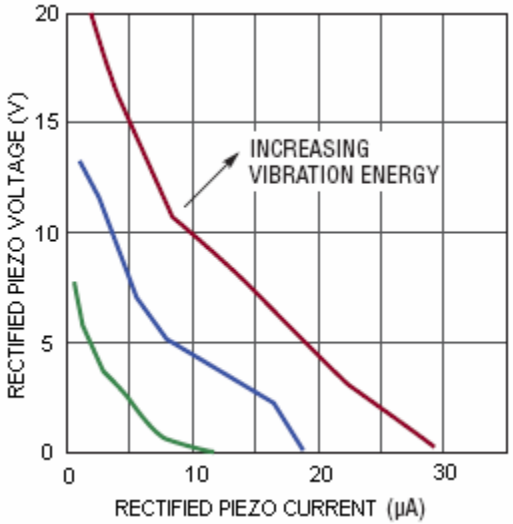
DC/DC Tradeoffs: Conversion Efficiency vs. Quiescent Current

V_{RECT} varies widely with vibration and load



Applications typically need a regulated supply



DC/DC Goals:

- Maximize conversion efficiency (Switching Converter)
- Minimize quiescent current (LDO)
- Key Consideration: Keep the application (V_{OUT}) powered at minimum vibration levels!

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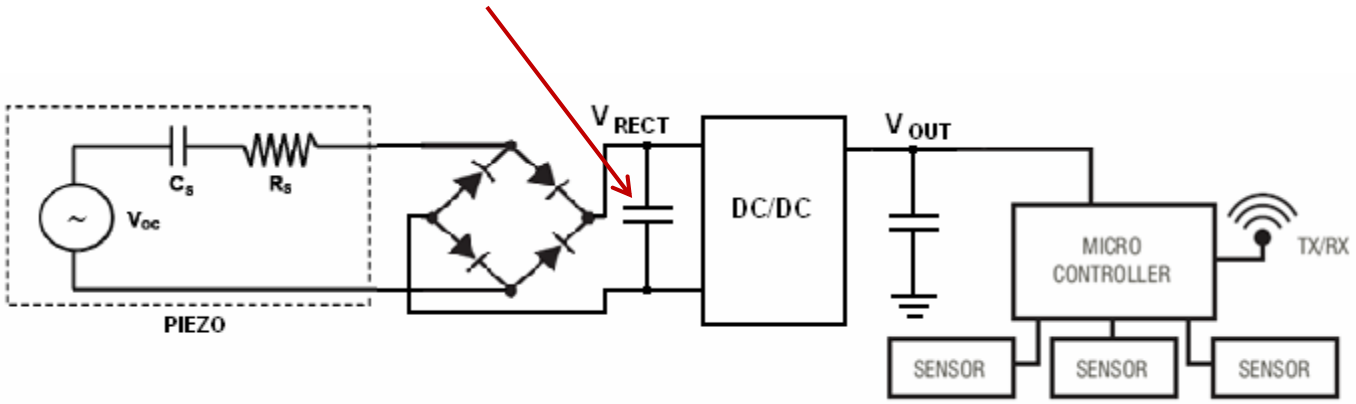
Charge Storage Considerations (1)

Energy Stored at DC/DC input



- PROs
  - Utilize high voltage energy storage ($E = ½ * C * V^2$)
  - High voltage ceramic capacitors (low leakage)
  - Combine with SuperCaps on the output for extended run times
- CONs
  - Higher vibration requirement to achieve high input voltage
  - Power from source not optimized by adjusting charge current

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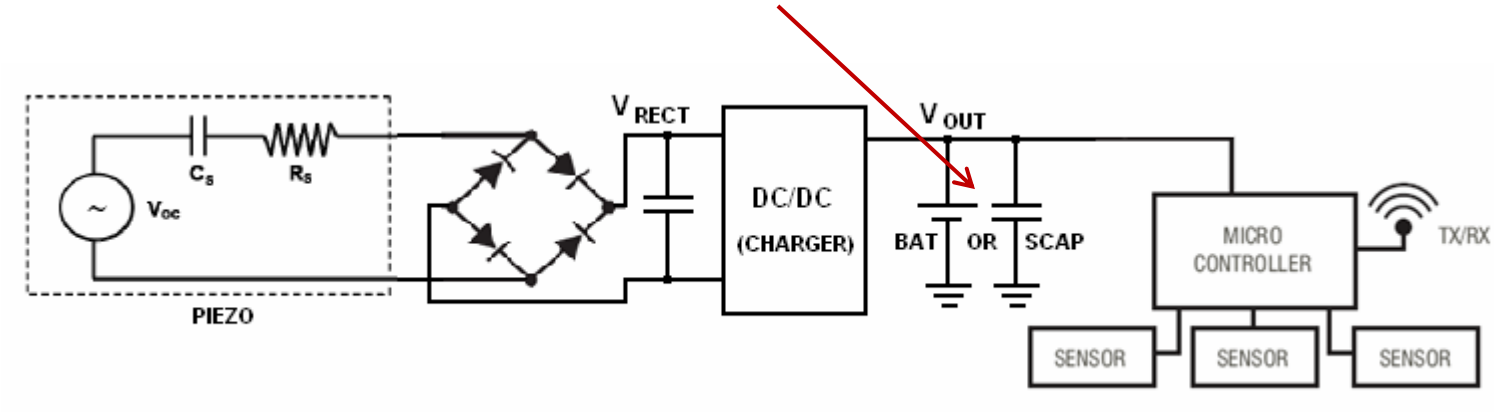
Charge Storage Considerations (2)

Energy Stored at DC/DC Output



- PROs
  - Low voltage energy storage allows use of low cost components
  - SuperCaps or batteries can be used at low voltages
  - Low vibration requirement due to low operating voltage
  - Modify charge current to optimize power output from source (MPPT…)
- CONs
  - Low voltage energy storage requires larger capacitance
  - Long charge times

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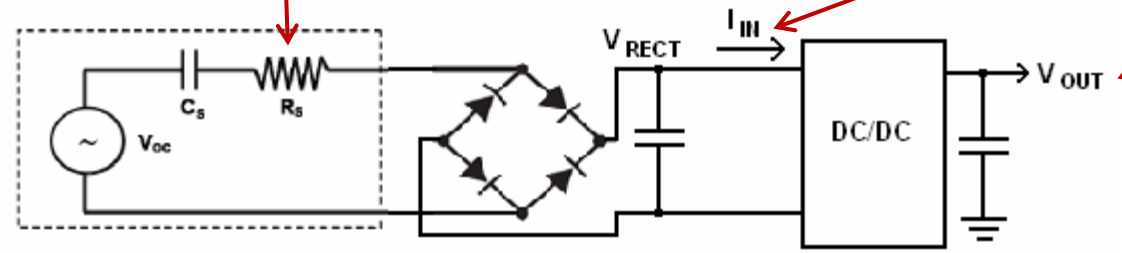
Start-Up Concerns

Piezo R_S is typically HIGH (10kOhm – 100kOhm+)

DC/DC operating current is highest at startup



Net Result:
V_{RECT} and V_{OUT} both stuck LOW!

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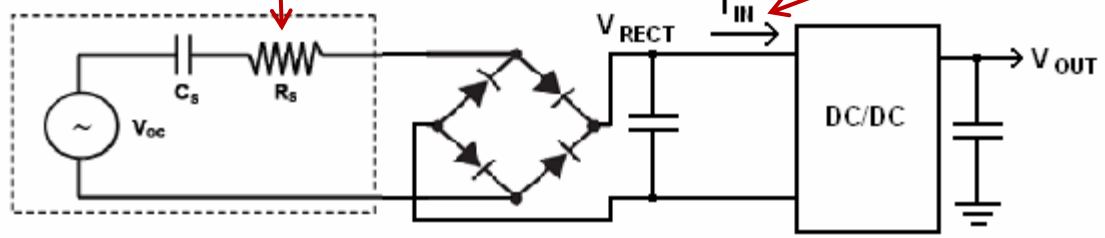

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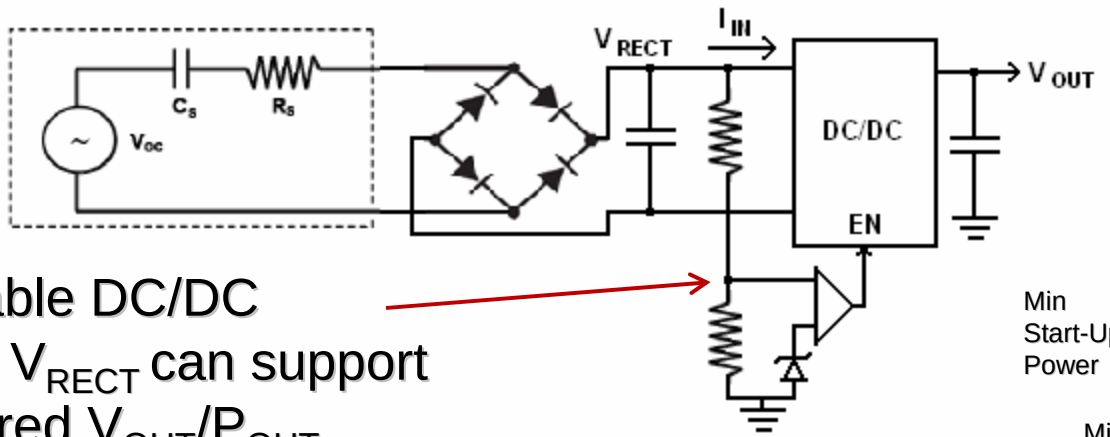
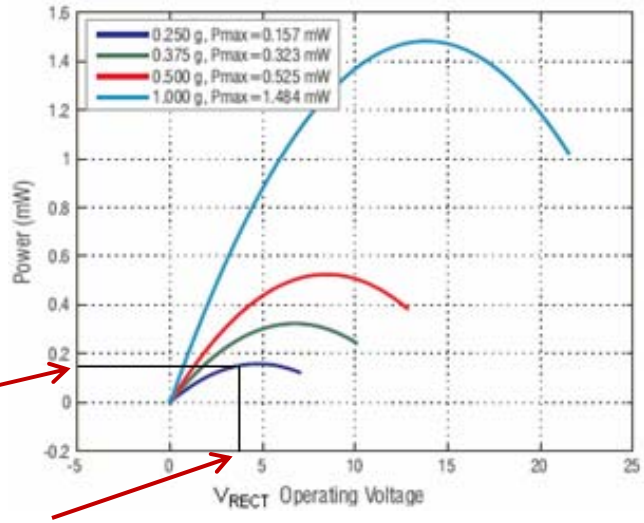
Simple Solution:



Disable DC/DC until V_{RECT} can support desired V_{OUT}/P_{OUT}



Min Start-Up Power

Min Start-Up Voltage

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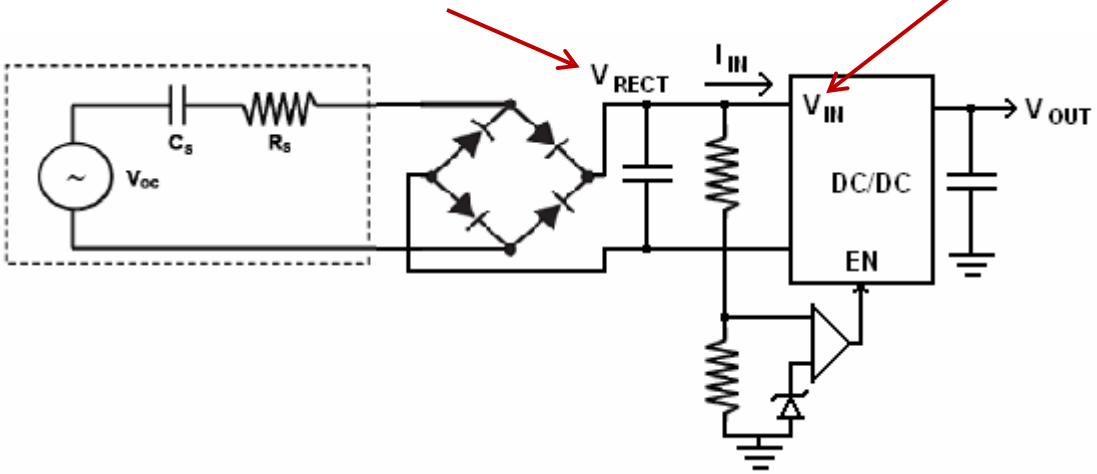
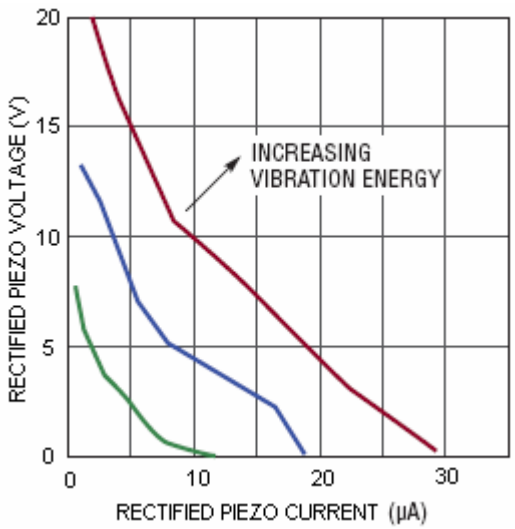
One More Problem: Overvoltage

V_{OC} and V_{RECT} climb at high vibration levels and low DC/DC load current

DC/DC's have max V_{IN} specs





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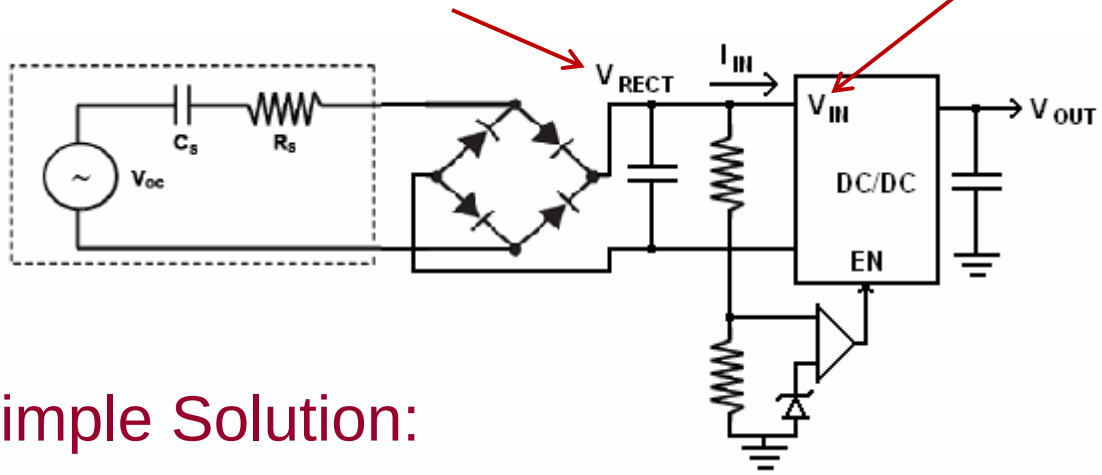
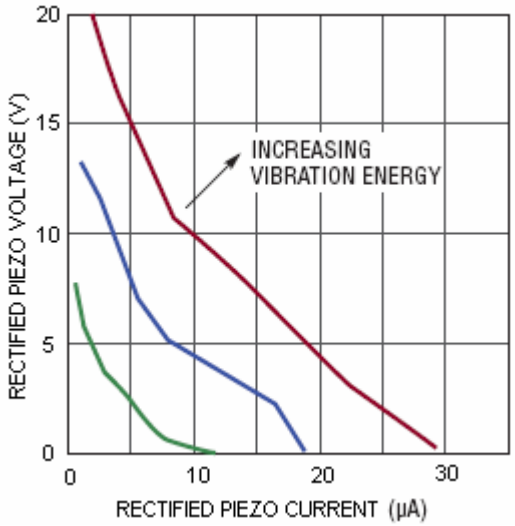
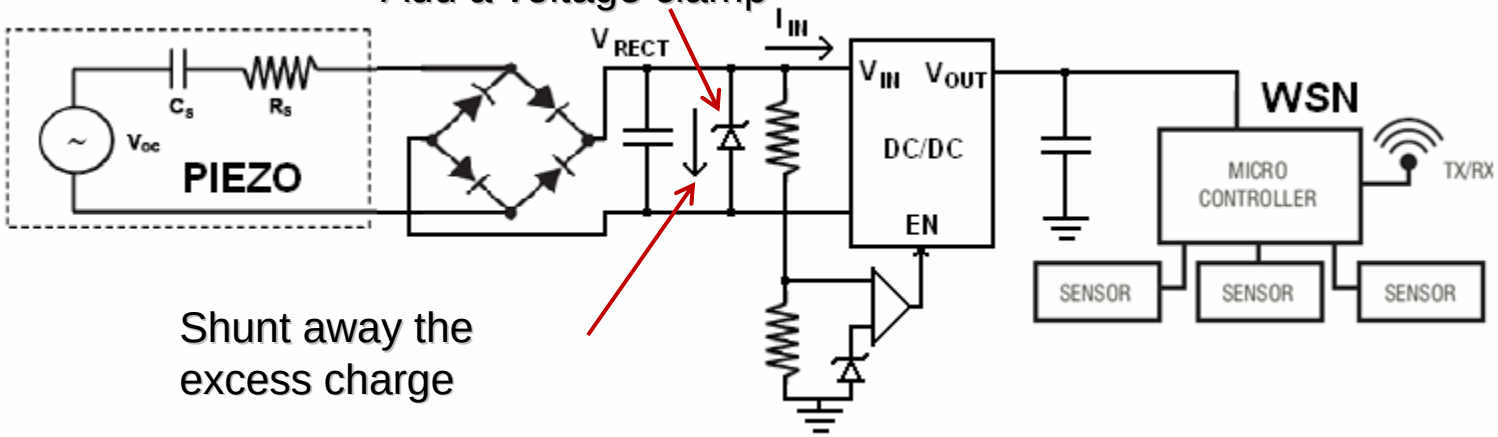




Simple Solution:

Add a voltage clamp



Shunt away the excess charge

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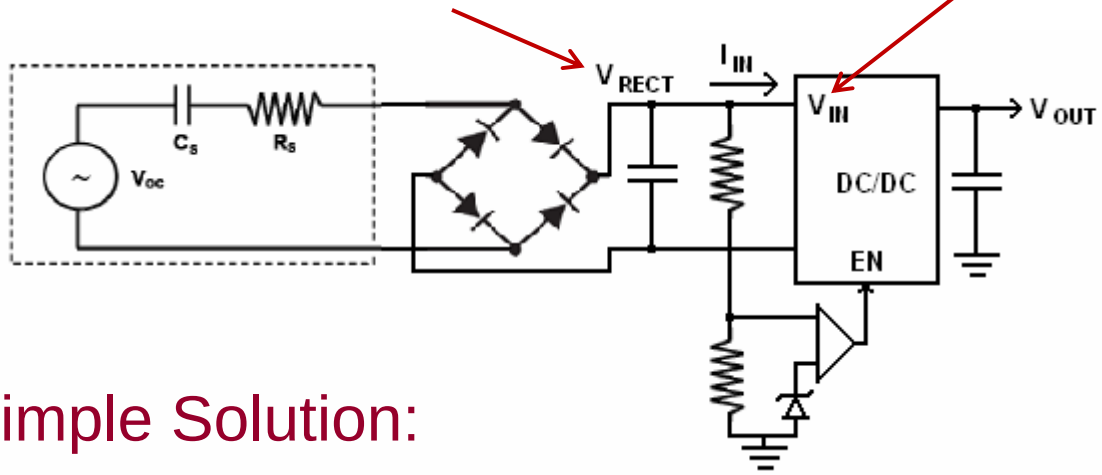

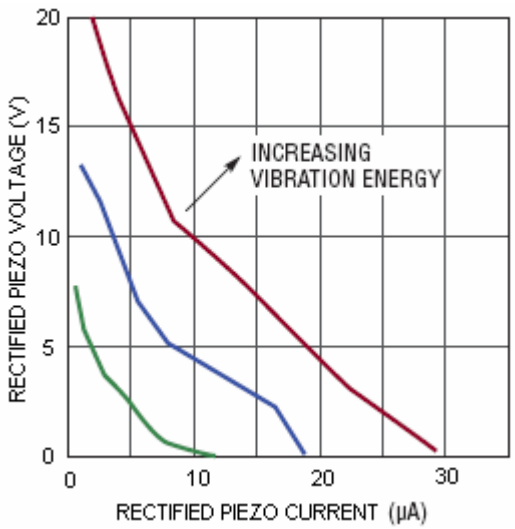

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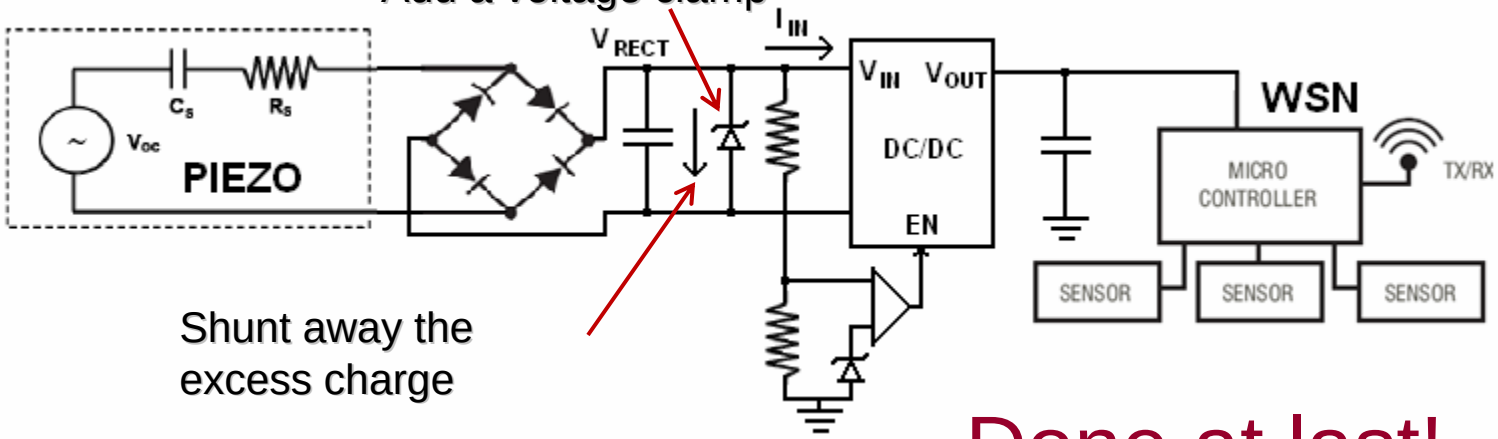

Shunt away the excess charge

Done at last!

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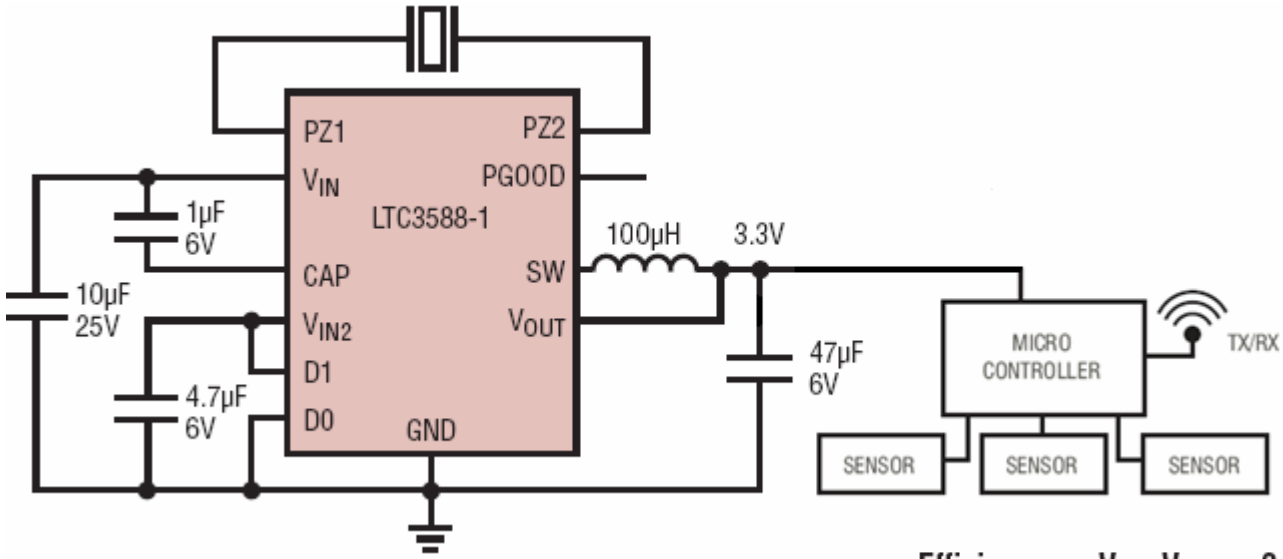
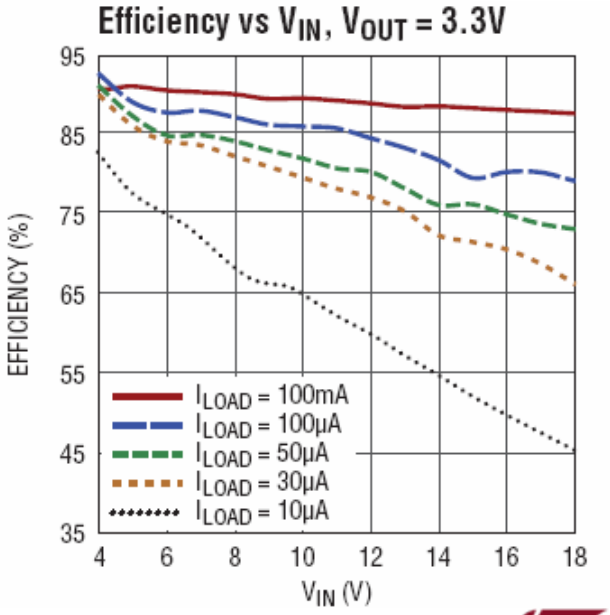
Integrated Solution: LTC3588 Piezoelectric Energy Harvester



Key Features:

- Integrated rectifier converts piezo AC output to DC
- UVLO circuit ensures reliable startup
- High efficiency synchronous step-down DC/DC
- V_{IN} Overvoltage protection shunt
- 1uA no load I_{CC} !!!



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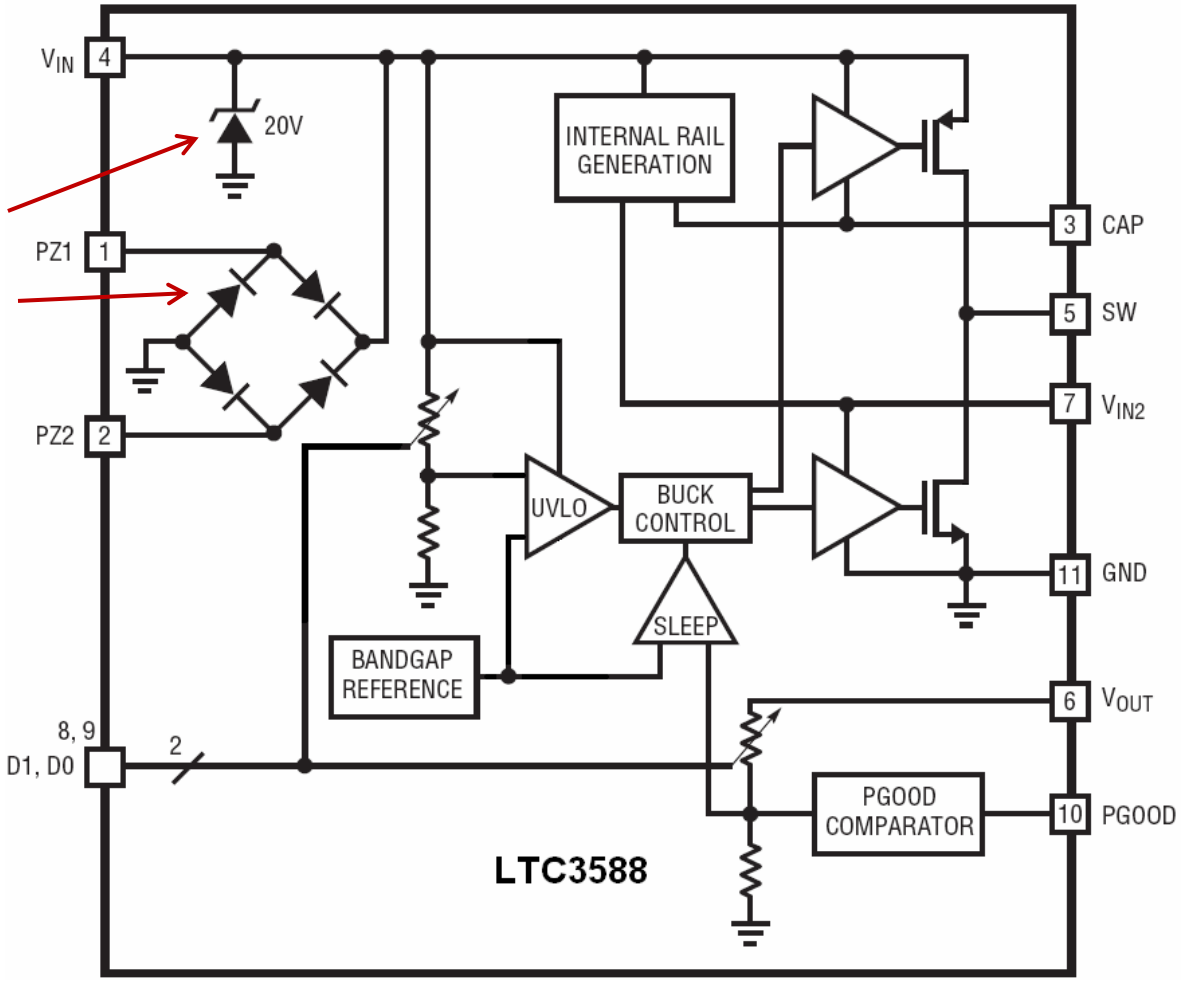
Performance Advantages of Integrated Solution

Low loss, low leakage diodes and transistors



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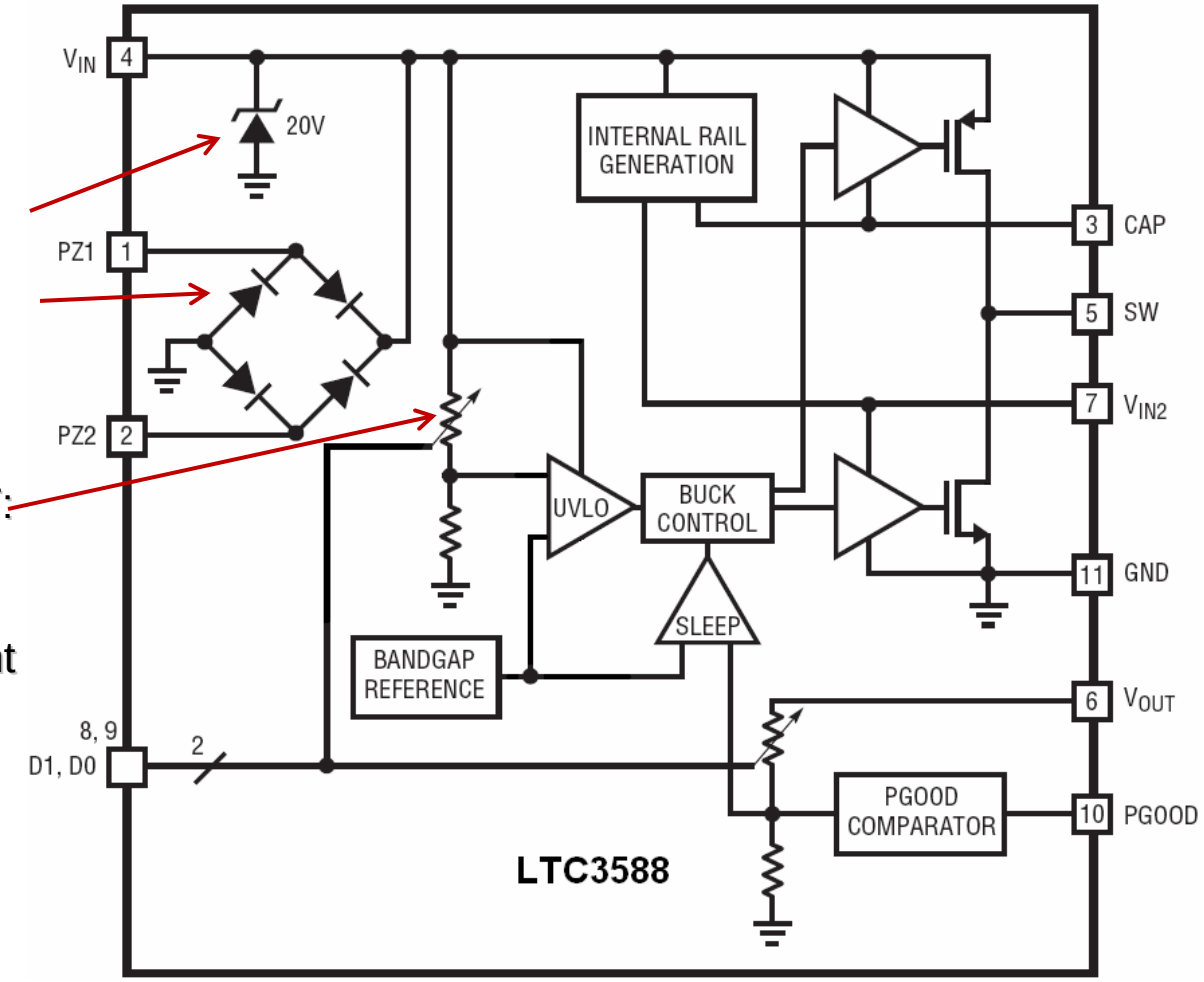
UVLO tracks VOUT: ensures start-up and/or peak operating point



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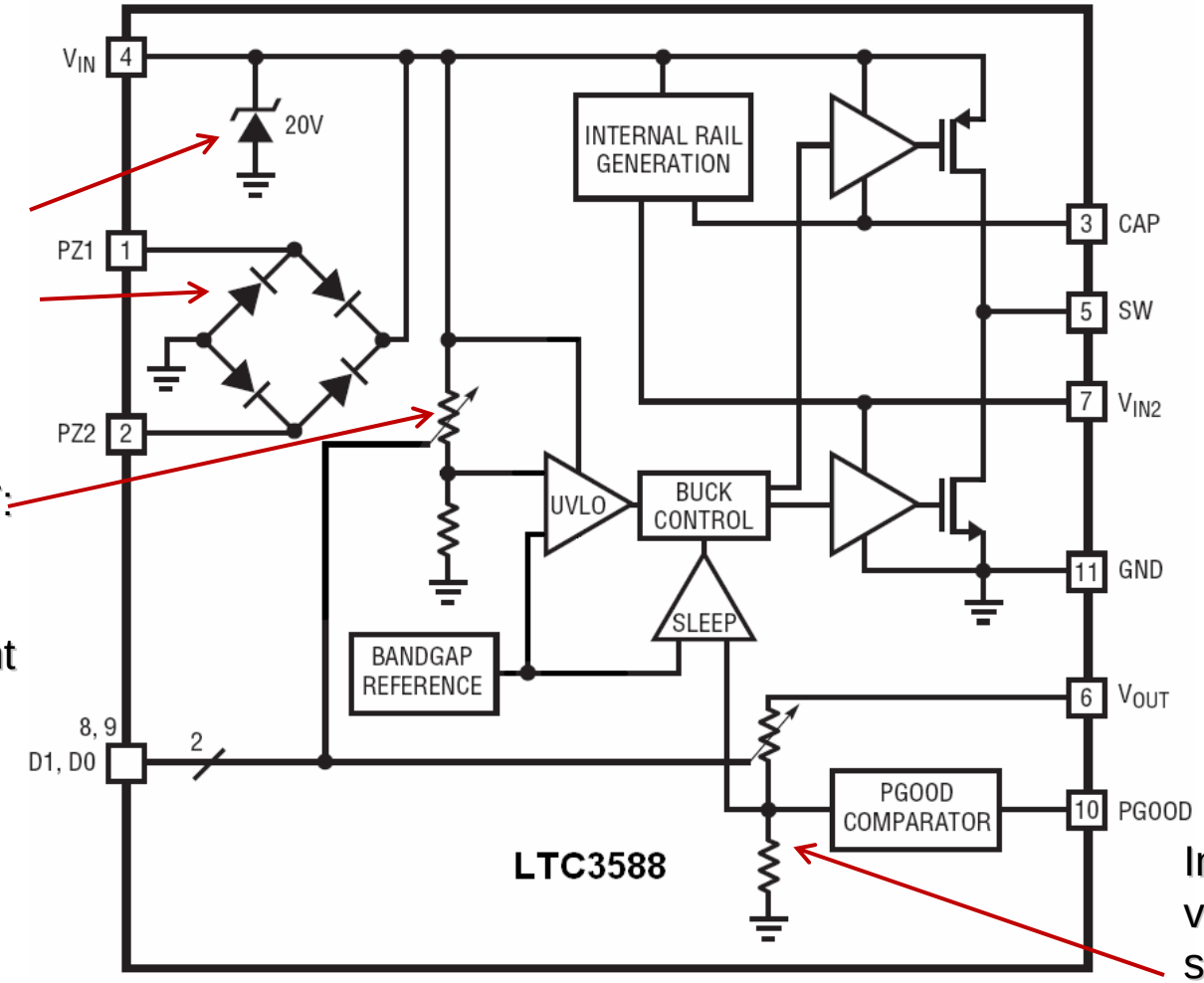

Internal high value R's not sensitive to PCB leakage

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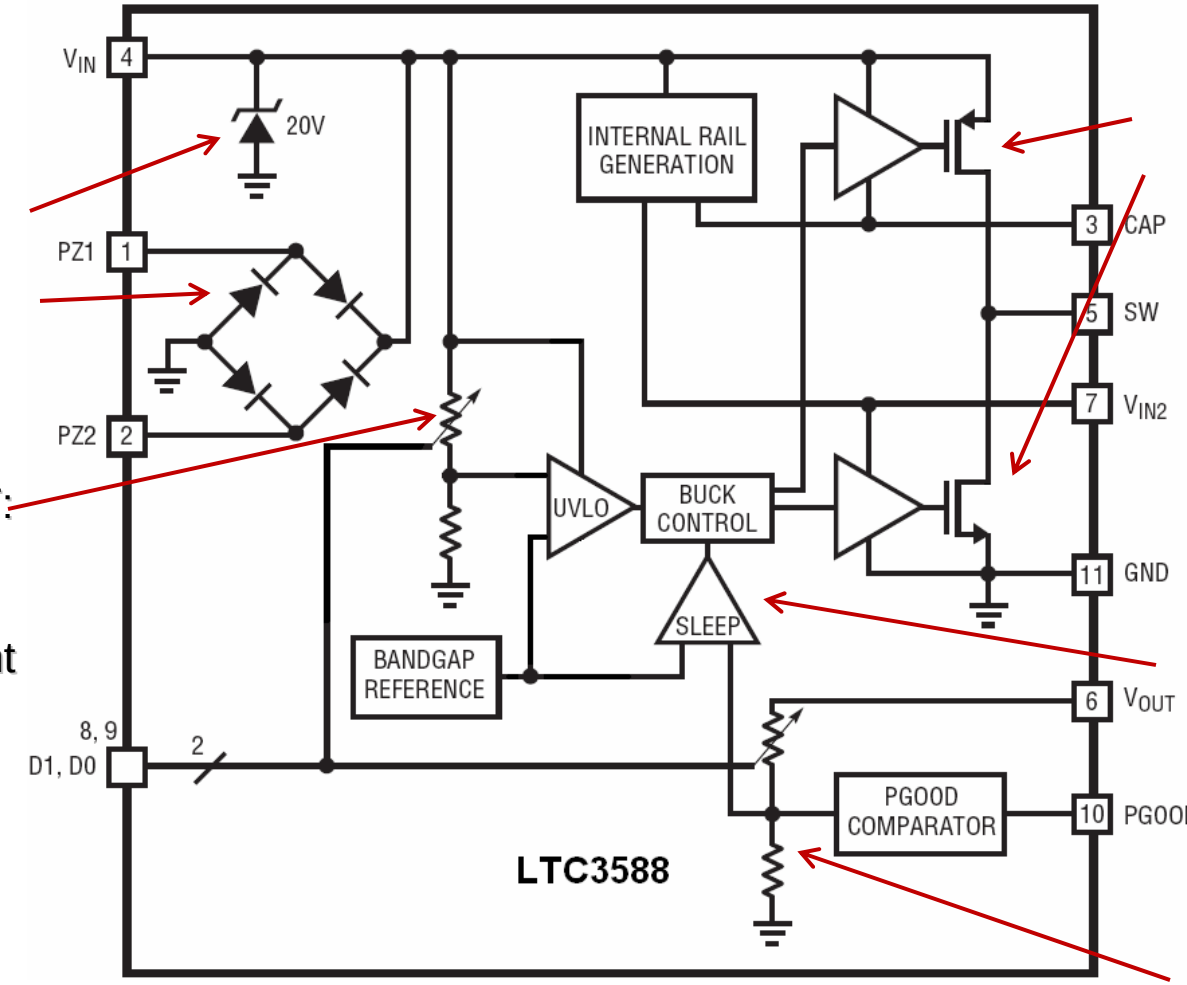

Power FETs optimized for load and operating conditions

Tiny devices provide fast response at very low currents

Internal high value R's not sensitive to PCB leakage

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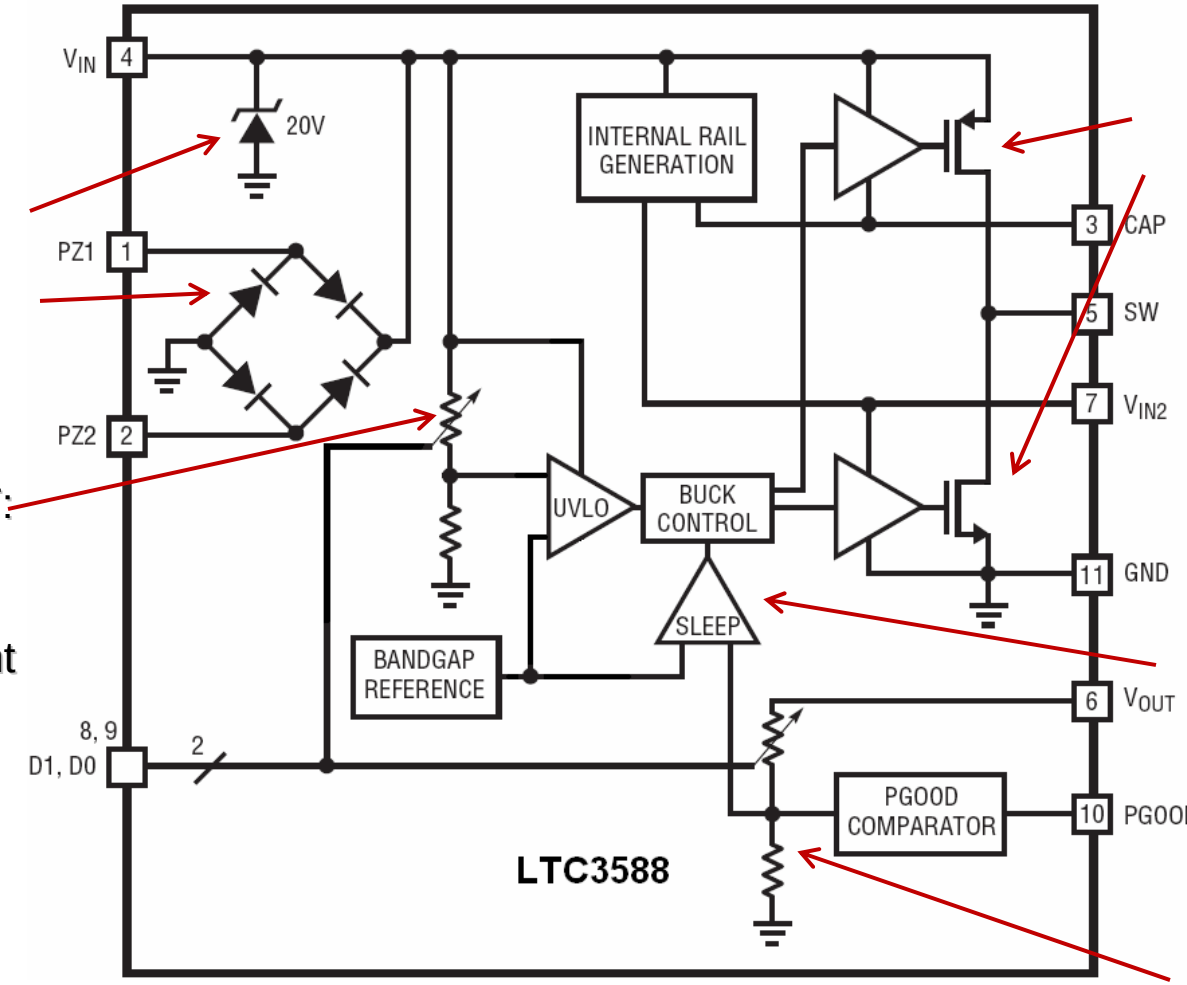

Power FETs optimized for load and operating conditions

Tiny devices provide fast response at very low currents

Internal high value R's not sensitive to PCB leakage

…this is very hard to do with discrete components!

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Summary - Energy Harvesting Trends

- Energy Harvesting applications are potentially everywhere
- Power needs of typical applications continue to drop
- Energy source characteristics determine transducer choice
- Reliable, regulated power achievable with properly designed system
- New Energy Harvesting ICs provide optimized solutions:

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

Thank You

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