# 7. Anexos

## Anexo I: Información acerca de los piezoeléctricos comprados y otros componentes.

| Producto | Distribuidor | Fabricante | Características |
|---|---|---|---|
| **20 unidades de 12mm, elementos piezoeléctricos, zumbador piezoeléctrico de cobre, sensor de sonido, disco de tambor y cable de cobre.** | Ali-HTI Store (China) | - | 12mm con cables voladores<br>Frecuencia de resonancia (KHz) 9,0 ±1 (Fs = 0)<br>Impedancia resonante (Ω) Rr≤500Ω<br>Capacitancia a 120Hz (NF) = 11±30%<br>Temperatura de funcionamiento (°)-20 ∽ + 70<br>Temperatura de almacenamiento (°)-30 ∽ + 80<br>Material: cobre de PVC<br>Tamaño: diámetro de la placa de Metal (mm): 12<br>longitud del Cable: 7 cm |
| **20 unidades de 15mm, piezoeléctrico zumbador eléctrico, tambor disco + alambre de cobre.** | ZT-HomeImprovement Store (China) | ZLinKJ | Se puede utilizar como altavoz/sirena cuando se pega a una superficie.<br>Se utiliza habitualmente como sensores de percusión en instrumentos musicales, almohadillas de tambor, kits, etc.<br>Diámetro: 15mm |
| **10 unidades de 20mm, cerámica piezoeléctrico, sensor de gatillo tambor disco + alambre de cobre, piezoeléctricos de timbre de cobre.** | N2HAO Party Store (China) | - | Material: cobre de PVC<br>Diámetro: 20mm<br>Discos piezoeléctricos para zumbador Sensor de presión altavoz |
| **10 unidades de 27mm, elementos de cerámica piezoeléctrica, zumbador de cobre.** | Tools Improving Store | HUXUAN | Chips de zumbador con cable de cobre<br>Se puede usar como altavoz/sonda cuando se pega a una superficie.<br>Comúnmente utilizado como sensores de percusión en instrumentos musicales, almohadillas de batería, kits, etc<br>Material: Metal<br>Diámetro: 27 mm |
| **10 unidades de 35mm, piezocerámico, piezoeléctrico zumbador de cobre, sensor.** | Sweetie Castle (China) | JETTING | Discos piezos para zumbador Sensor de presión altavoz DIY<br>Material: cobre de PVC<br>Tamaño: diámetro de la placa de Metal (mm): 35<br>Longitud del Cable: 11 cm |
| **1 unidad de 35mm, cerámica piezoeléctrica de material PZT, nueva generación de energía, bimorph.** | Vector Trading Company (China, Hunan) | - | Tensión de salida: 0-30 v DC<br>Corriente de salida: 0-10mA<br>Impedancia de resonancia: 100 oHm<br>Directo de capacitancia: 43-48 nF<br>Material de sustrato: Latón# CW617N<br>Kt = 0,48 eT33 = 2600<br>Qm = 80 Kp = 0,62<br>D33> 580x10-12C/N<br>Kt33 = 2900 |

| | | | |
|---|---|---|---|
| **LDT0-028K piezoeléctrico sensor de vibración piezoeléctricos de película delgada, de alta sensibilidad, acoplamiento AC.** | BETTERSHENGSUN SHENGSUN Store (China, Guangdong) | BETTERSHENGSUN | LDT0-028K, buena flexibilidad del sensor, película piezoeléctrica de 28 mm, electrodo de pasta de plata con impresión de pantalla, película laminada en el sustrato de poliéster de 0.125mm. Cuando la película piezoeléctrica sufre fuerza externa en la dirección vertical, producirá una alta tensión de salida. Con el efecto directo puede ser un interruptor flexible.<br>Añadir bloques de masa o cambiar la longitud libre del elemento puede afectar la frecuencia y sensibilidad del sensor. Se puede producir a baja frecuencia.<br>Soldadura terminal de conexión<br>Hay un bloque de masa/masa.<br>Excelente resistencia al impacto<br>Temperatura de funcionamiento: 0-85 grados C<br>Temperatura de almacenamiento: -40-85 grados C<br>La alta temperatura LDT puede soportar 125 grados C<br>Interruptor de activación de baja potencia<br>Bajo costo sensor de vibración |
| **Generación de energía de cerámica piezoeléctrica rectangular, protección del medio ambiente. Bimorph PZT.** | Hennybig Fish Store (China) | - | 60*20mm<br>Tensión de salida: 0-52 v CCCorriente de salida: 0-28mA<br>Impedancia de resonancia: <81 oHm<br>Directo de capacitancia: 139-191 nF<br>Material de sustrato: Kover #4J36De cerámica piezoeléctrica material: P5-13B<br>Kt = 0,45 eT33 = 1800<br>Qm = 800 Kp> 0.85%<br>D33> 850x10-12C/N Kt33 = 4800<br>T = 0,18mm T1 = 0,16mm t2 = 0,16mm |

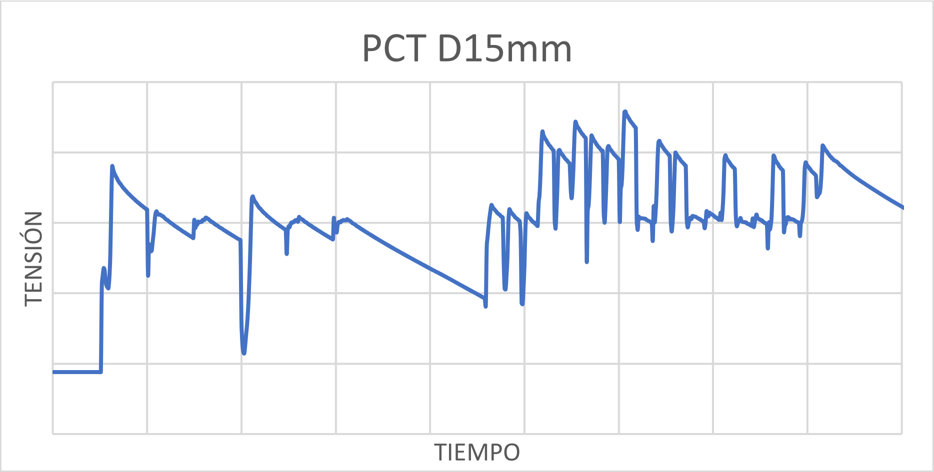
*Tabla 19: Características de piezoeléctricos seleccionados.*

| Nº del Fabricante | Fabricante | Descripción | Precio por unidad en Mouser |
|---|---|---|---|
| **TAP106M025SCS** | AVX | Capacitadores de tantalio - Con plomo **sólido,** 25V, 10uF, 20% y ESR=2.5 Ohms | 0,75 € |
| **GRM32EE70J107ME15L** | Murata | Condensadores de cerámica multicapa (SMD), 100uF, 6.3volts | 0,76 € |

*Tabla 20: Componentes utilizados.*

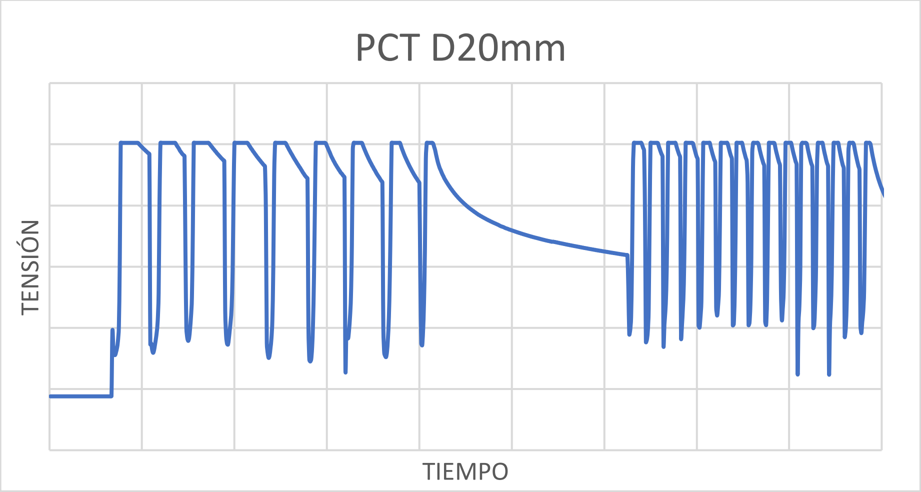
## Anexo II: Gráficas.

- Medidas para la caracterización de los piezoeléctricos con LabJack:



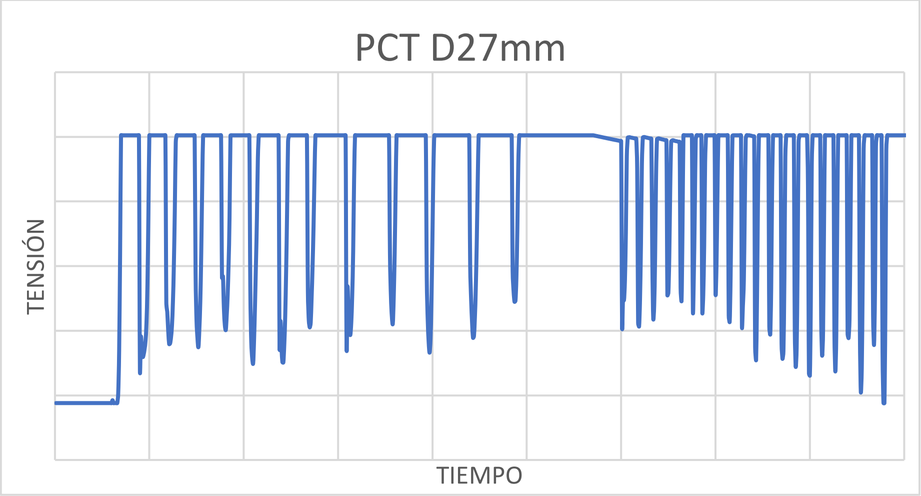
*Gráfica 15: Medidas del PCT D15mm con LabJack T7-PRO.*

- ○ En la **Gráfica 15** vemos la respuesta del PCT de diámetro **15mm**. Primero con pulsos (golpeando con el dedo el piezoeléctrico) más lentos (que simularían la acción de caminar) y luego más rápidos (que simularían la acción de correr), ambas respuestas son picos muy irregulares. Respuesta **muy similar** para el piezoeléctrico de **12mm**.



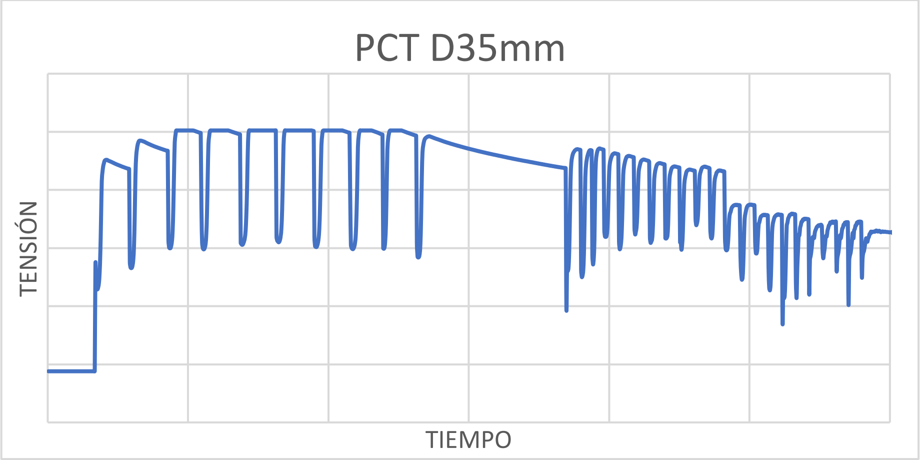
*Gráfica 16: Medidas del PCT D20mm con LabJack T7-PRO.*

- ○ En la **Gráfica 16** vemos la respuesta del PCT de diámetro **20mm**. Para ambos casos, pulsos lentos y rápidos, los piscos son **más regulares y anchos** que en los casos anteriores.



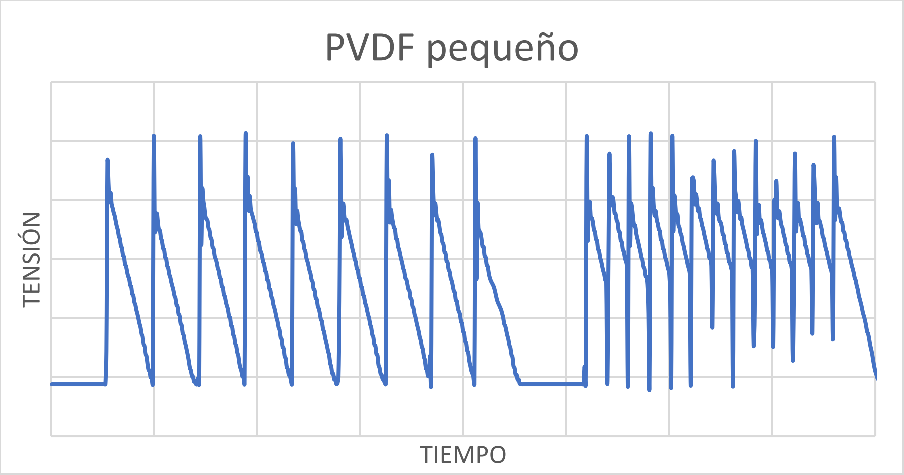
*Gráfica 17: Medidas del PCT D27mm con LabJack T7-PRO.*

- En la **Gráfica 17** vemos la respuesta del PCT de diámetro **27mm**. En ambos casos los picos son ya **muy regulares y más anchos** que en los casos anteriores.



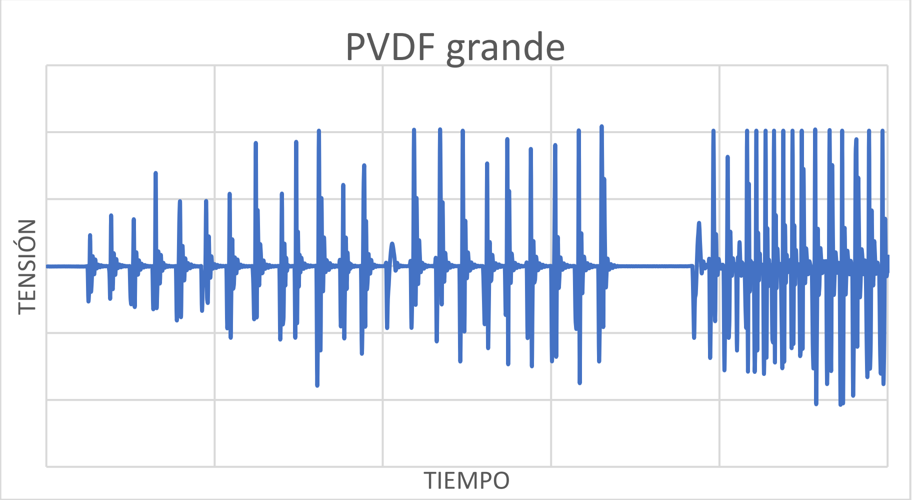
*Gráfica 18: Medidas del PCT D35mm con LabJack T7-PRO.*

- En la **Gráfica 18** vemos la respuesta del PCT de diámetro **35mm**. Para pulsos lentos se mantienen regulares, pero para pulsos más rápidos son **algo irregulares**.



*Gráfica 19: Medidas del PVDF pequeño con LabJack T7-PRO.*

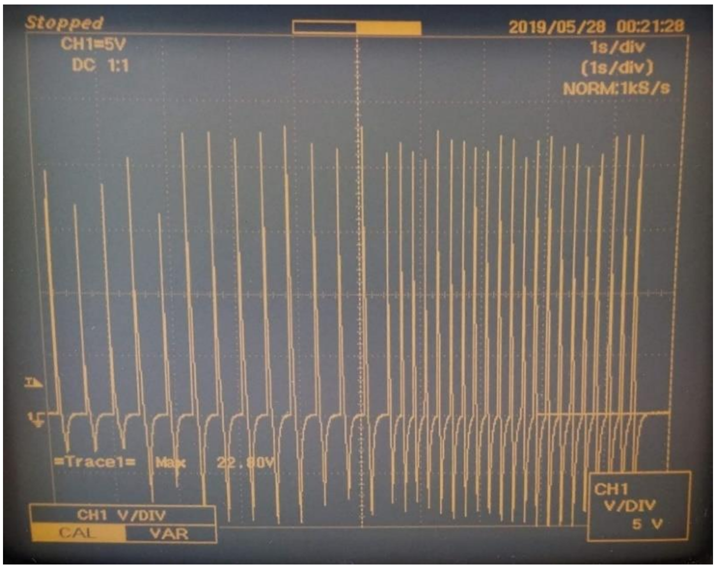
- En la **Gráfica 19** vemos la respuesta del PVDF **pequeño**, Para ambos casos los picos son bastante regulares, pero **no muy anchos**.



*Gráfica 20: Medidas del PVDF grande con LabJack T7-PRO.*

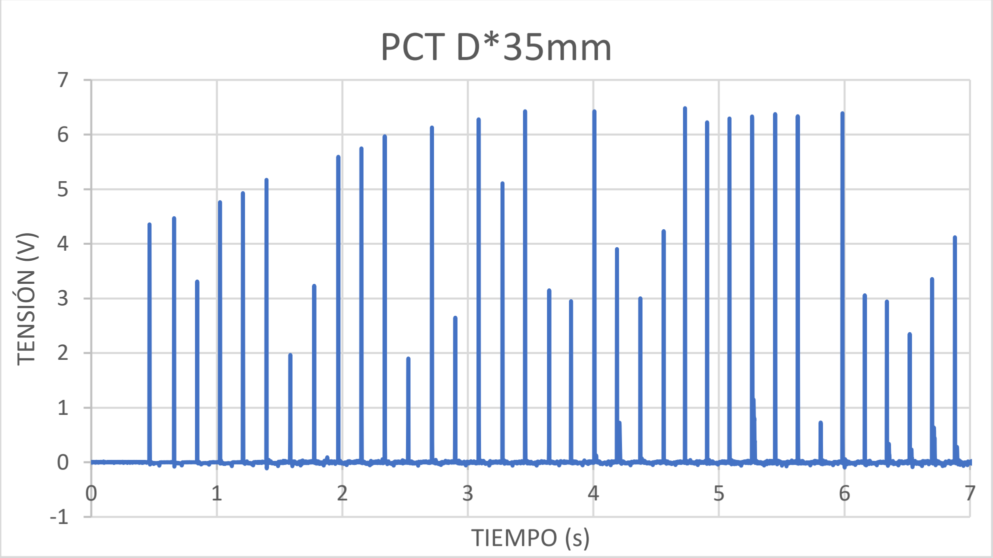
- En la **Gráfica 20** vemos la respuesta del PVDF **grande**. Para pulsos más rápidos los picos son **más regulares**, pero en ambos casos no son muy anchos.

- Medidas para la caracterización de los piezoeléctricos con osciloscopio:



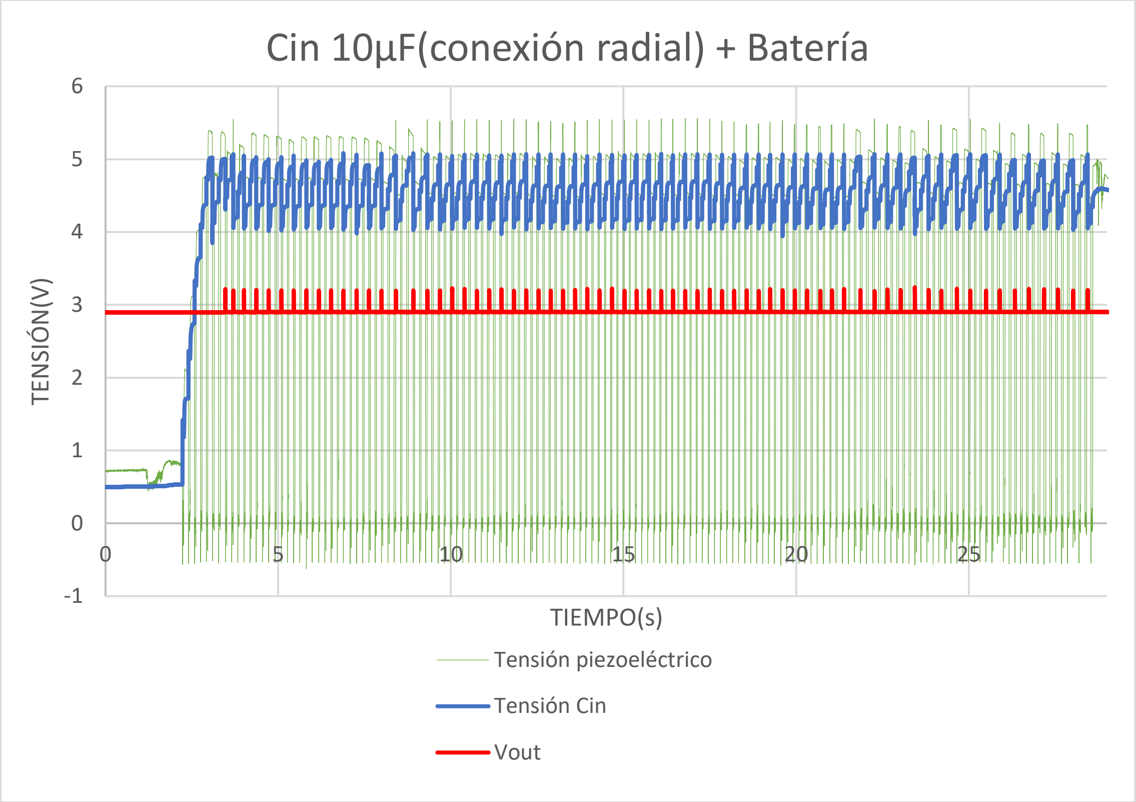
*Gráfica 21: Medidas del PCT D27mm con osciloscopio.*

- En la **Gráfica 21** vemos la respuesta del PCT de diámetro **27mm**, el osciloscopio está configurado a 5V/división. Los picos de tensión tanto para pulsos lentos como rápidos son muy regulares y tienen una amplitud de -10 a 22V.



*Gráfica 22: Medidas del PTC D35mm más caro conectado al circuito, con LabJack T7-PRO.*

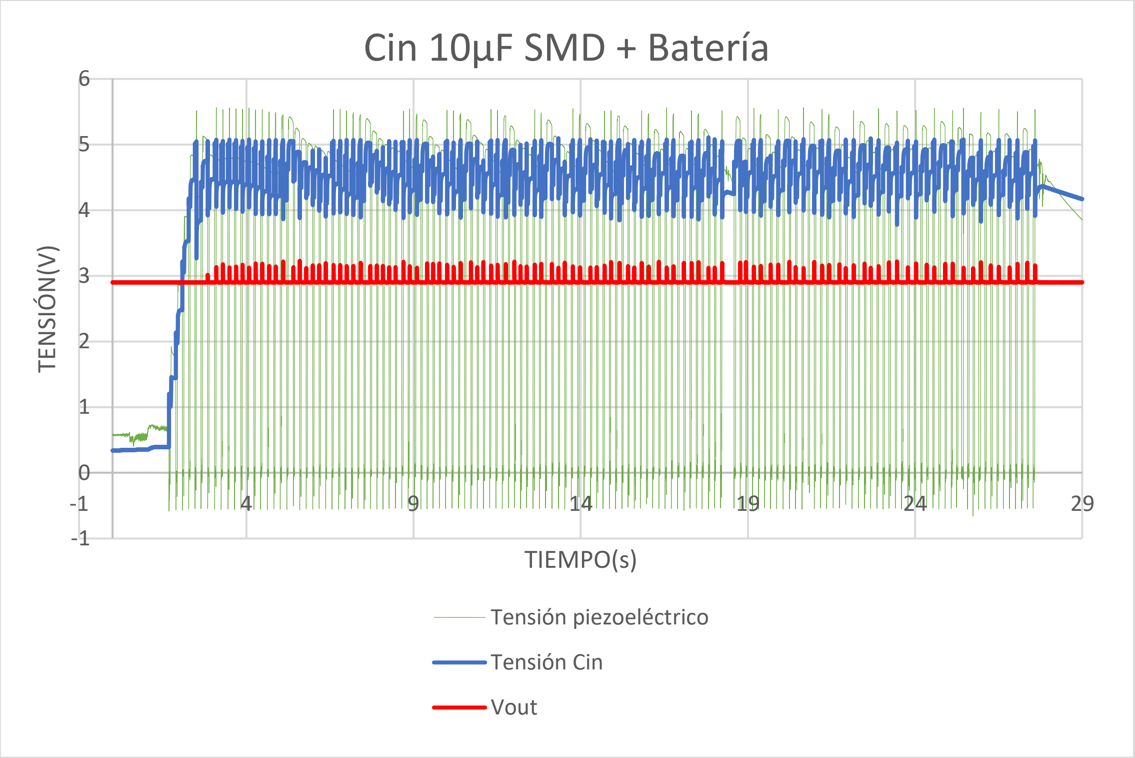
- Mediciones:
  - Para un $C_{IN}$ **de Tantalio de 10 µF y 25 V con conexión radial** (TAP106M025SCS, Anexo I), no podemos apreciar en la **Gráfica 23** como sube la tensión de la batería, pero podremos comparar los picos que aparecen en esta con los diferentes $C_{IN}$.
    La carga de la batería tras 29s es de **1.264mV**.



v

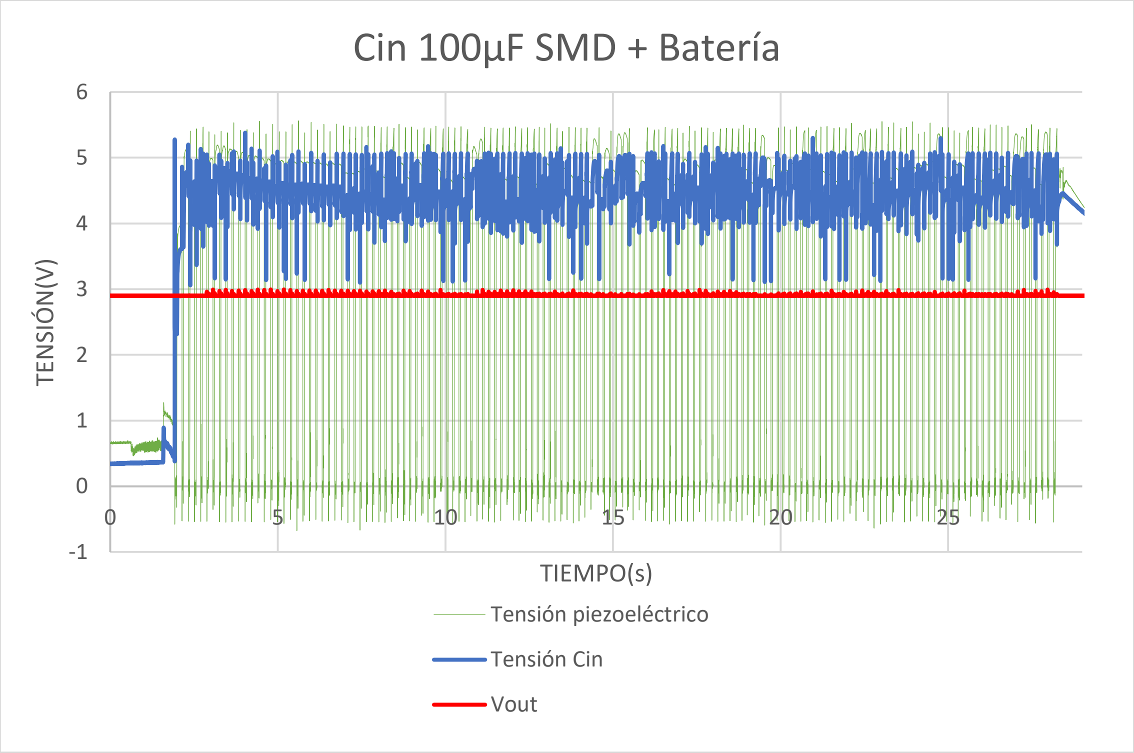
*Gráfica 23: Medición con $C_{IN}$=10µF con terminales de conexión, $Batería$ y PCT D35mm más caro, con LabJack T7-PRO.*

○ Para un $C_{IN}$ **SMD de cerámica multicapa de 10µF y 25V** (GRM21BR61E106MA73L, Anexo I), en la **Gráfica 24** vemos que los picos de carga son más frecuentes que en el caso anterior, debido a que este condensador tiene menos pérdidas por lo que alcanza antes la tensión de transferencia.
La carga de la batería tras 29s es de **1.58mV**, **mayor que en el caso anterior** en consecuencia de lo que acabamos de comentar.



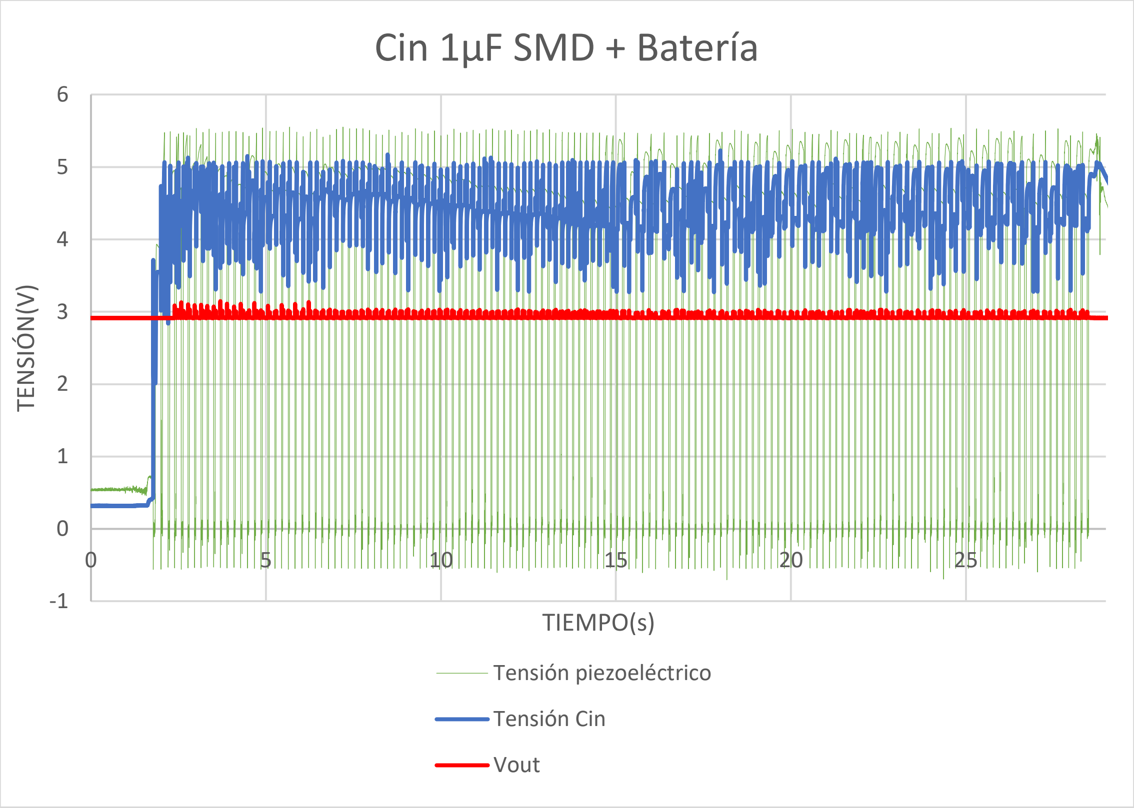
*Gráfica 24: Medición con $C_{IN}$=10µF SMD, Batería y PCT D35mm más caro, con LabJack T7-PRO.*

- Para un **$C_{IN}$ SMD de cerámica multicapa de 100µF y 6.3V** (GRM32EE70J107ME15L, Anexo I), en la **Gráfica 25** vemos que los picos de carga son más anchos que en los casos anteriores, debido a que este condensador es más grande por lo que la energía que transfiere es mayor, pero lo hará con menos frecuencia.
  La carga de la batería tras 29s es de **0.632mV**, menor que en los casos anteriores dado que el condensador, al ser más grande, tarda más en alcanzar la tensión de transferencia, por lo que la frecuencia de estas es menor, y las pérdidas mayores.



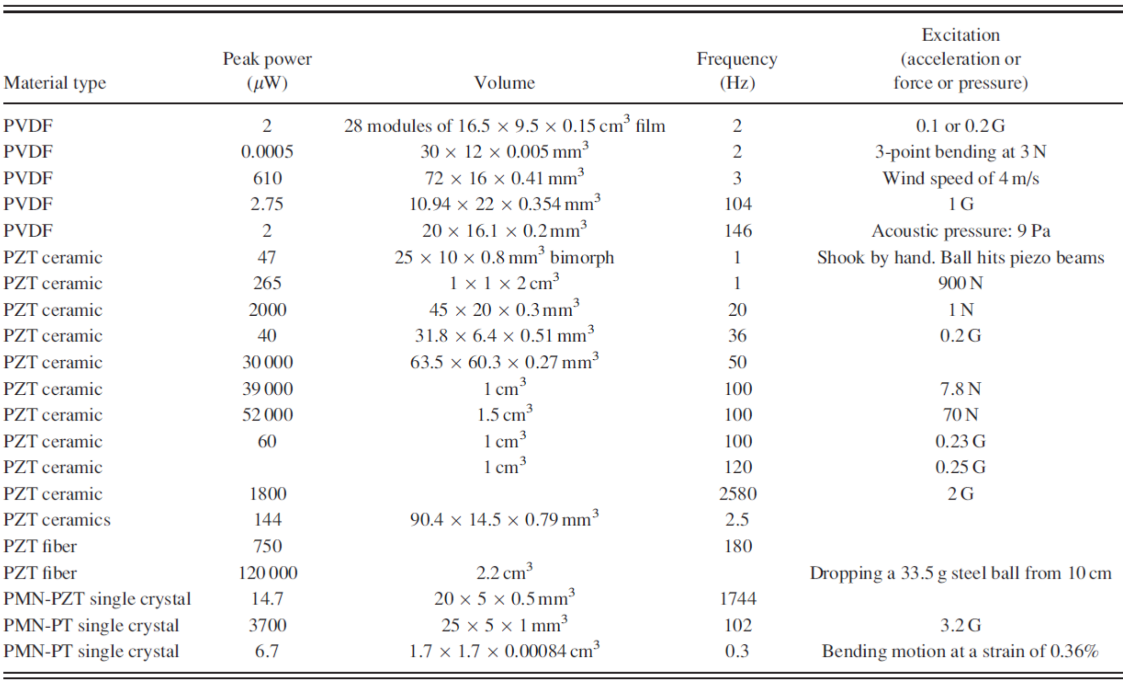
*Gráfica 25: Medición con $C_{IN}$=100µF SMD, Batería y PCT D35mm más caro, con LabJack T7-PRO.*

- Dado que los resultados reflejan que las situaciones más favorables se dan con el menor condensador, 10µF, probamos con uno de **1µF SMD** del laboratorio. En la **Gráfica 26** vemos que los picos de carga son aún más frecuentes que en el caso de 10µF, debido a que este condensador es más pequeño por lo que alcanza antes la tensión de transferencia.
  La carga de la batería tras 29s es de **0.948mV**, mayor que en el caso de 100µF como esperábamos, pero **menor que con 10uF**. Esto puede ser por que las características de este condensador (del laboratorio) son peores que los anteriores que hemos probado (pedidos específicamente).



*Gráfica 26: Medición con $C_{IN}$=1µF SMD, Batería y PCT D35mm más caro, con LabJack T7-PRO.*

# Anexo III: Ilustraciones y Tablas.



| Material type | Peak power ($\mu$W) | Volume | Frequency (Hz) | Excitation (acceleration or force or pressure) |
|---|---|---|---|---|
| PVDF | 2 | 28 modules of 16.5 × 9.5 × 0.15 $cm^3$ film | 2 | 0.1 or 0.2 G |
| PVDF | 0.0005 | 30 × 12 × 0.005 $mm^3$ | 2 | 3-point bending at 3 N |
| PVDF | 610 | 72 × 16 × 0.41 $mm^3$ | 3 | Wind speed of 4 m/s |
| PVDF | 2.75 | 10.94 × 22 × 0.354 $mm^3$ | 104 | 1 G |
| PVDF | 2 | 20 × 16.1 × 0.2 $mm^3$ | 146 | Acoustic pressure: 9 Pa |
| PZT ceramic | 47 | 25 × 10 × 0.8 $mm^3$ bimorph | 1 | Shook by hand. Ball hits piezo beams |
| PZT ceramic | 265 | 1 × 1 × 2 $cm^3$ | 1 | 900 N |
| PZT ceramic | 2000 | 45 × 20 × 0.3 $mm^3$ | 20 | 1 N |
| PZT ceramic | 40 | 31.8 × 6.4 × 0.51 $mm^3$ | 36 | 0.2 G |
| PZT ceramic | 30 000 | 63.5 × 60.3 × 0.27 $mm^3$ | 50 | |
| PZT ceramic | 39 000 | 1 $cm^3$ | 100 | 7.8 N |
| PZT ceramic | 52 000 | 1.5 $cm^3$ | 100 | 70 N |
| PZT ceramic | 60 | 1 $cm^3$ | 100 | 0.23 G |
| PZT ceramic | | 1 $cm^3$ | 120 | 0.25 G |
| PZT ceramic | 1800 | | 2580 | 2 G |
| PZT ceramics | 144 | 90.4 × 14.5 × 0.79 $mm^3$ | 2.5 | |
| PZT fiber | 750 | | 180 | |
| PZT fiber | 120 000 | 2.2 $cm^3$ | | Dropping a 33.5 g steel ball from 10 cm |
| PMN-PZT single crystal | 14.7 | 20 × 5 × 0.5 $mm^3$ | 1744 | |
| PMN-PT single crystal | 3700 | 25 × 5 × 1 $mm^3$ | 102 | 3.2 G |
| PMN-PT single crystal | 6.7 | 1.7 × 1.7 × 0.00084 $cm^3$ | 0.3 | Bending motion at a strain of 0.36% |

*Tabla 21: Recolectores de energía piezoeléctrica. (Li, Tian, & Deng, 2014)*

*Ilustración 31: LabJack T7-PRO. (labjack)*

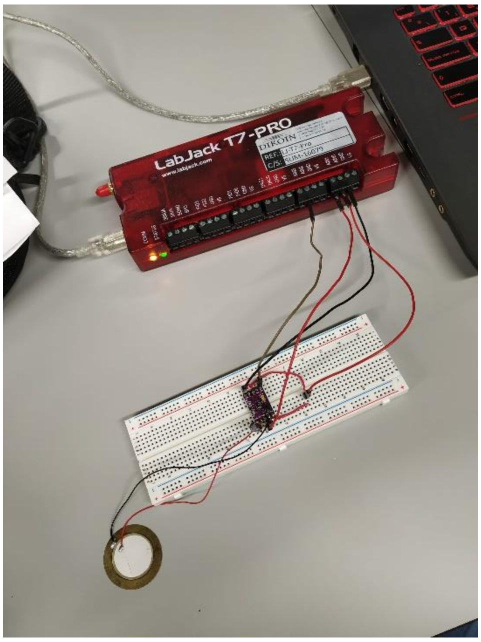
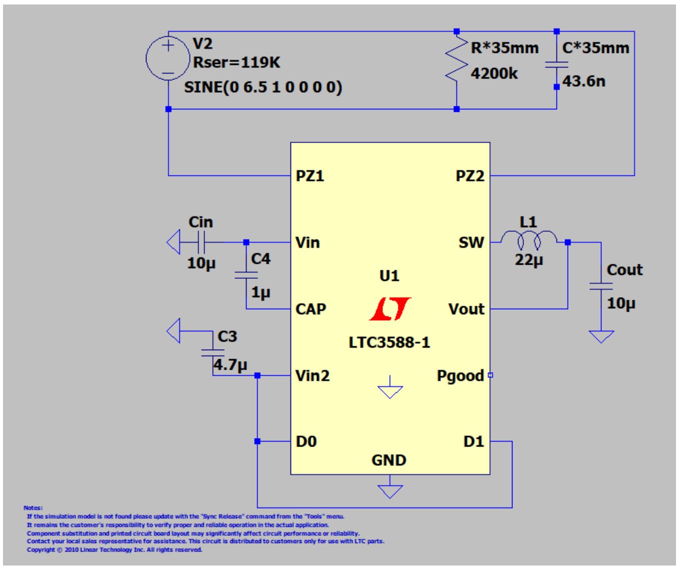


*Ilustración 32: Montaje del módulo con el piezo.*



Notes:
If the simulation model is not found please update with the "Sync Release" command from the "Tools" menu.
It remains the customer's responsibility to verify proper and reliable operation in the actual application.
Component substitution and printed circuit board layout may significantly affect circuit performance or reliability.
Contact your local sales representative for assistance. This circuit is distributed to customers only for use with LTC parts.
Copyright © 2010 Linear Technology Inc. All rights reserved.

*Ilustración 33: Circuito de simulación en LTspice XVII.*

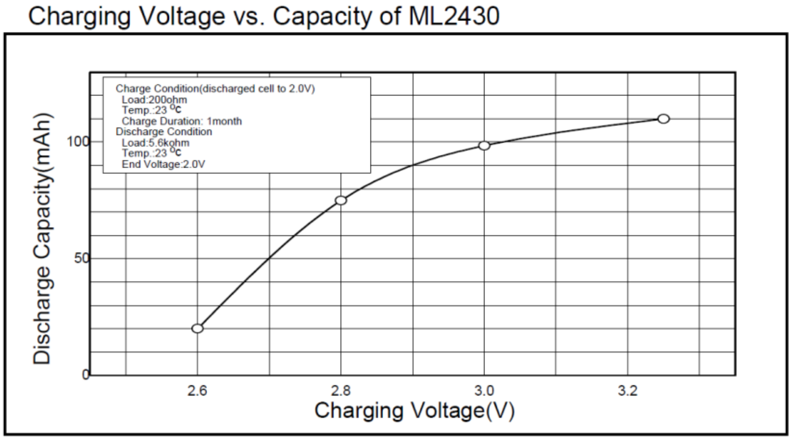
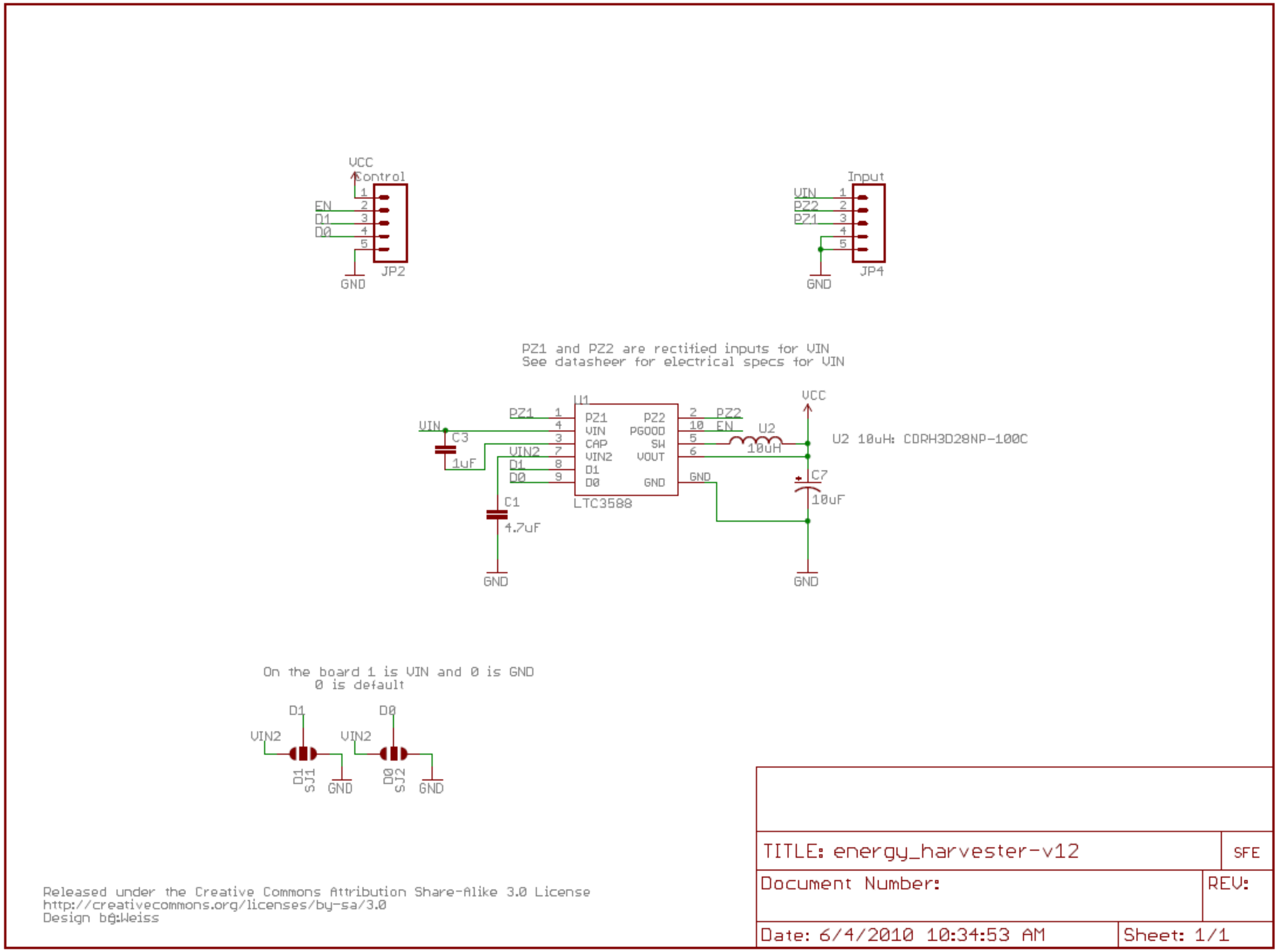
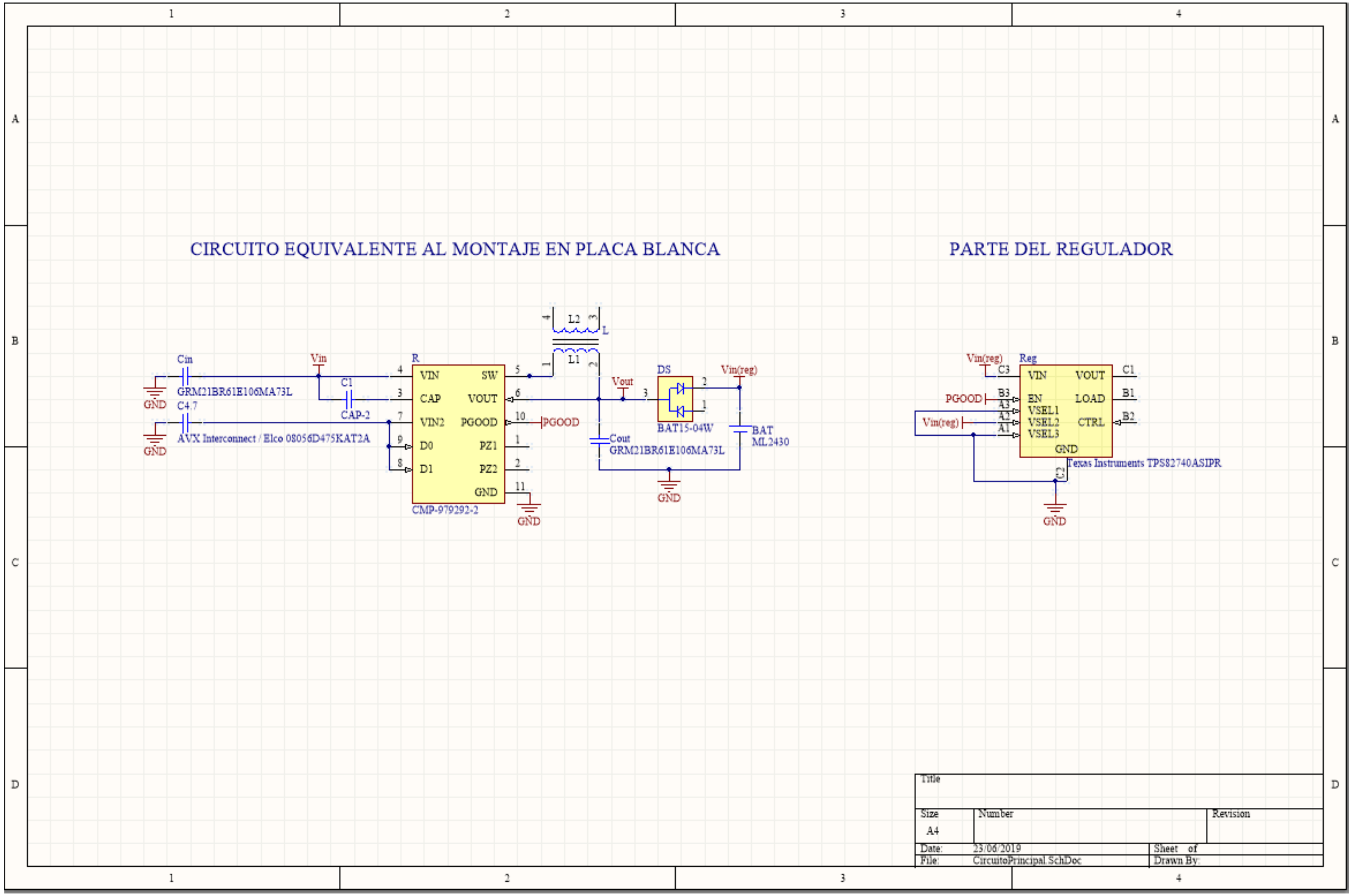


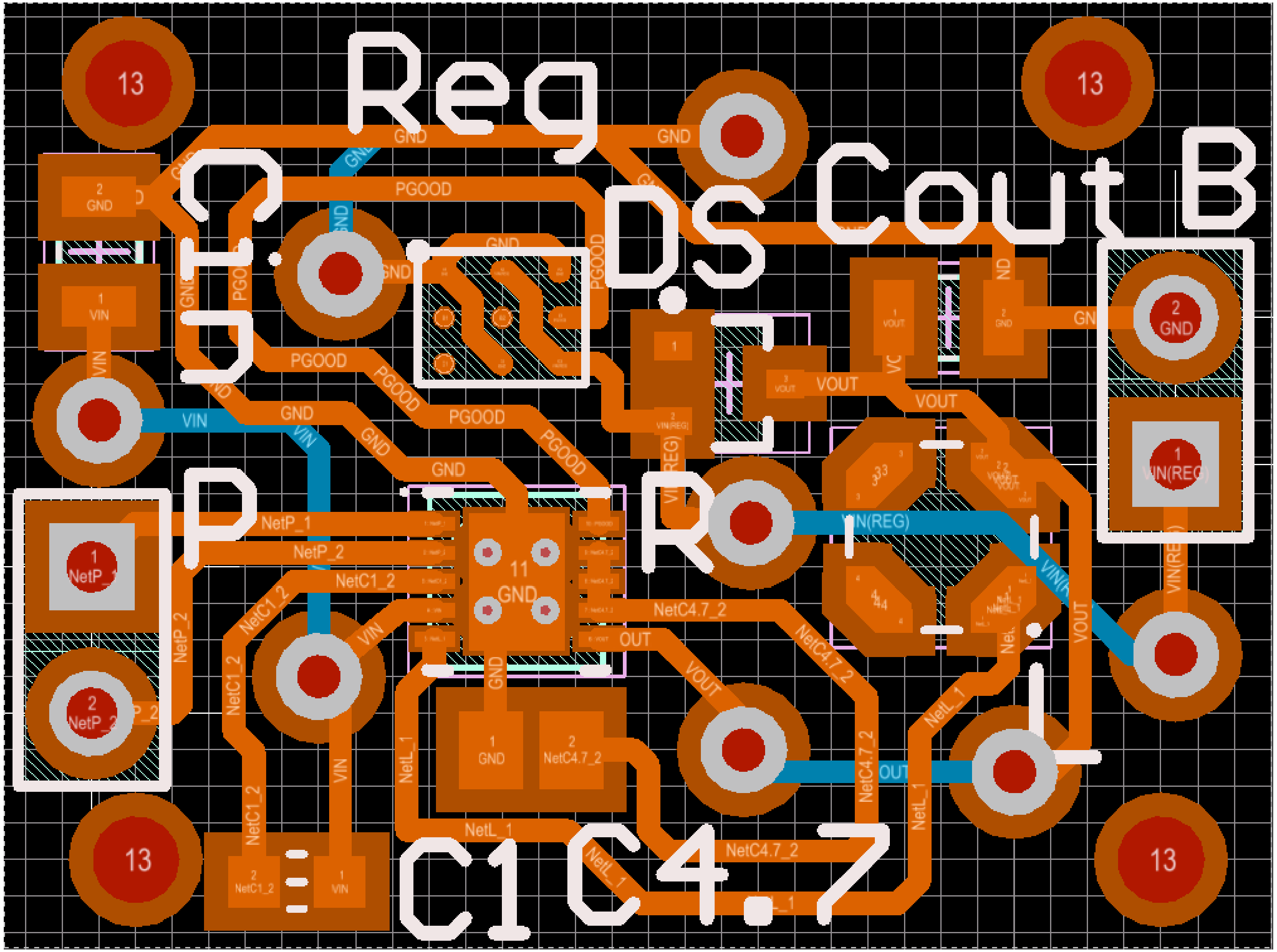
*Ilustración 34: Capacidad frente a tensión de carga de la batería ML2430.*

## Anexo IV: Esquemático del módulo del LTC3588-1



# Anexo V: Planos del esquemático y PCB




Reg
DS
Cout
B
P
R
C1
C4.7
13
GND
PGOOD
VIN
VOUT
VIN(REG)
NetP_1
NetP_2
NetC1_2
NetC4.7_2
NetL_1
OUT
11
GND

# Anexo VI: *Datasheet* LTC3588-1

# Nanopower Energy Harvesting Power Supply

## FEATURES

- **950nA Input Quiescent Current (Output in Regulation – No Load)**
- **450nA Input Quiescent Current in UVLO**
- **2.7V to 20V Input Operating Range**
- **Integrated Low-Loss Full-Wave Bridge Rectifier**
- **Up to 100mA of Output Current**
- **Selectable Output Voltages of 1.8V, 2.5V, 3.3V, 3.6V**
- High Efficiency Integrated Hysteretic Buck DC/DC
- Input Protective Shunt – Up to 25mA Pull-Down at $V_{IN} \geq 20V$
- Wide Input Undervoltage Lockout (UVLO) Range
- Available in 10-Lead MSE and 3mm × 3mm DFN Packages

## APPLICATIONS

- Piezoelectric Energy Harvesting
- Electro-Mechanical Energy Harvesting
- Wireless HVAC Sensors
- Mobile Asset Tracking
- Tire Pressure Sensors
- Battery Replacement for Industrial Sensors
- Remote Light Switches
- Standalone Nanopower Buck Regulator

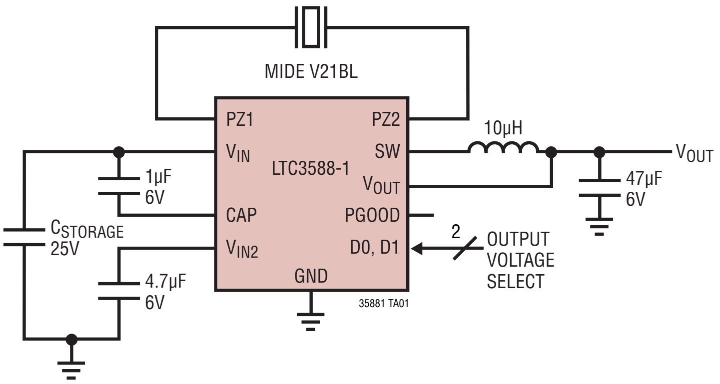
## DESCRIPTION

The LTC®3588-1 integrates a low-loss full-wave bridge rectifier with a high efficiency buck converter to form a complete energy harvesting solution optimized for high output impedance energy sources such as piezoelectric, solar, or magnetic transducers. An ultralow quiescent current undervoltage lockout (UVLO) mode with a wide hysteresis window allows charge to accumulate on an input capacitor until the buck converter can efficiently transfer a portion of the stored charge to the output. In regulation, the LTC3588-1 enters a sleep state in which both input and output quiescent currents are minimal. The buck converter turns on and off as needed to maintain regulation.

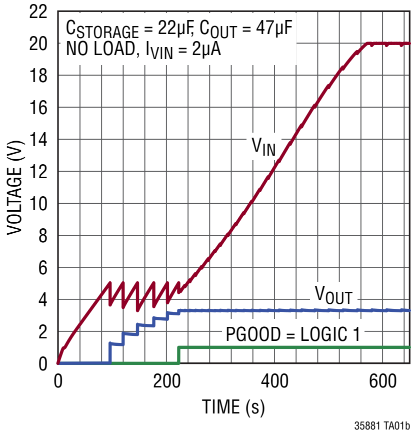
Four output voltages, 1.8V, 2.5V, 3.3V and 3.6V, are pin selectable with up to 100mA of continuous output current; however, the output capacitor may be sized to service a higher output current burst. An input protective shunt set at 20V enables greater energy storage for a given amount of input capacitance.

## TYPICAL APPLICATION

**100mA Piezoelectric Energy Harvesting Power Supply**



**LTC3588-1 3.3V Regulator Start-Up Profile**



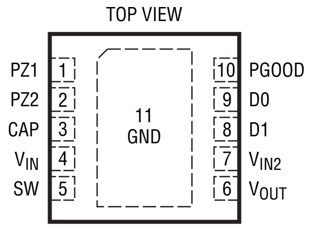
## ABSOLUTE MAXIMUM RATINGS (Note 1)

$V_{IN}$
  Low Impedance Source ........................ –0.3V to 18V*
  Current Fed, $I_{SW}$ = 0A ................................ 25mA†
PZ1, PZ2 ....................................................... 0V to $V_{IN}$
D0, D1 .............. –0.3V to [Lesser of ($V_{IN2}$ + 0.3V) or 6V]
CAP ...................... [Higher of –0.3V or ($V_{IN}$ – 6V)] to $V_{IN}$
$V_{IN2}$ ................... –0.3V to [Lesser of ($V_{IN}$ + 0.3V) or 6V]

* $V_{IN}$ has an internal 20V clamp
† For t < 1ms and Duty Cycle < 1%,
Absolute Maximum Continuous Current = 5mA

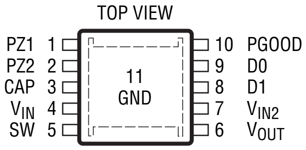
$V_{OUT}$ .................... –0.3V to Lesser of ($V_{IN2}$ + 0.3V) or 6V
PGOOD .............. –0.3V to Lesser of ($V_{OUT}$ + 0.3V) or 6V
$I_{PZ1}$, $I_{PZ2}$ ............................................................ ±50mA
$I_{SW}$ ................................................................... 350mA
Operating Junction Temperature Range
(Notes 2, 3) ............................................... –40 to 125°C
Storage Temperature Range ...................... –65 to 150°C
Lead Temperature (Soldering, 10 sec)
  MSE Only ......................................................... 300°C

## PIN CONFIGURATION



DD PACKAGE
10-LEAD (3mm × 3mm) PLASTIC DFN

$T_{JMAX}$ = 125°C, $\theta_{JA}$ = 43°C/W, $\theta_{JC}$ = 7.5°C/W
EXPOSED PAD (PIN 11) IS GND, MUST BE SOLDERED TO PCB



MSE PACKAGE
10-LEAD PLASTIC eMSOP

$T_{JMAX}$ = 125°C, $\theta_{JA}$ = 45°C/W, $\theta_{JC}$ = 10°C/W
EXPOSED PAD (PIN 11) IS GND, MUST BE SOLDERED TO PCB

## ORDER INFORMATION

| LEAD FREE FINISH | TAPE AND REEL | PART MARKING* | PACKAGE DESCRIPTION | TEMPERATURE RANGE |
|---|---|---|---|---|
| LTC3588EDD-1#PBF | LTC3588EDD-1#TRPBF | LFKY | 10-Lead (3mm × 3mm) Plastic DFN | –40°C to 125°C |
| LTC3588IDD-1#PBF | LTC3588IDD-1#TRPBF | LFKY | 10-Lead (3mm × 3mm) Plastic DFN | –40°C to 125°C |
| LTC3588EMSE-1#PBF | LTC3588EMSE-1#TRPBF | LTFKX | 10-Lead Plastic eMSOP | –40°C to 125°C |
| LTC3588IMSE-1#PBF | LTC3588IMSE-1#TRPBF | LTFKX | 10-Lead Plastic eMSOP | –40°C to 125°C |

Consult LTC Marketing for parts specified with wider operating temperature ranges. *The temperature grade is identified by a label on the shipping container.

For more information on lead free part marking, go to: http://www.linear.com/leadfree/
This product is only offered in trays. For more information go to: http://www.linear.com/packaging/

## ELECTRICAL CHARACTERISTICS

**The ● denotes the specifications which apply over the full operating junction temperature range, otherwise specifications are for $T_A$ = 25°C. (Note 2) $V_{IN}$ = 5.5V unless otherwise specified.**

| SYMBOL | PARAMETER | CONDITIONS | | MIN | TYP | MAX | UNITS |
|---|---|---|---|---|---|---|---|
| $V_{IN}$ | Input Voltage Range | Low Impedance Source on $V_{IN}$ | ● | | | 18.0 | V |
| $I_{VIN}$ | $V_{IN}$ Quiescent Current | | | | | | |
| | UVLO | $V_{IN}$ = 2.5V, Not PGOOD | | | 450 | 700 | nA |
| | Buck Enabled, Sleeping | $V_{IN}$ = 4.5V | | | 950 | 1500 | nA |
| | Buck Enabled, Sleeping | $V_{IN}$ = 18V | | | 1.7 | 2.5 | μA |
| | Buck Enabled, Not Sleeping | $I_{SW}$ = 0A (Note 4) | | | 150 | 250 | μA |
| $V_{UVLO}$ | $V_{IN}$ Undervoltage Lockout Threshold | $V_{IN}$ Rising | | | | | |
| | | 1.8V Output Selected; D1 = 0, D0 = 0 | ● | 3.77 | 4.04 | 4.30 | V |
| | | 2.5V Output Selected; D1 = 0, D0 = 1 | ● | 3.77 | 4.04 | 4.30 | V |
| | | 3.3V Output Selected; D1 = 1, D0 = 0 | ● | 4.73 | 5.05 | 5.37 | V |
| | | 3.6V Output Selected; D1 = 1, D0 = 1 | ● | 4.73 | 5.05 | 5.37 | V |
| | | $V_{IN}$ Falling | | | | | |
| | | 1.8V Output Selected; D1 = 0, D0 = 0 | ● | 2.66 | 2.87 | 3.08 | V |
| | | 2.5V Output Selected; D1 = 0, D0 = 1 | ● | 2.66 | 2.87 | 3.08 | V |
| | | 3.3V Output Selected; D1 = 1, D0 = 0 | ● | 3.42 | 3.67 | 3.91 | V |
| | | 3.6V Output Selected; D1 = 1, D0 = 1 | ● | 3.75 | 4.02 | 4.28 | V |
| $V_{SHUNT}$ | $V_{IN}$ Shunt Regulator Voltage | $I_{VIN}$ = 1mA | | 19.0 | 20.0 | 21.0 | V |
| $I_{SHUNT}$ | Maximum Protective Shunt Current | 1ms Duration | | 25 | | | mA |
| | Internal Bridge Rectifier Loss ($\|V_{PZ1} – V_{PZ2}\| – V_{IN}$) | $I_{BRIDGE}$ = 10μA | | 350 | 400 | 450 | mV |
| | Internal Bridge Rectifier Reverse Leakage Current | $V_{REVERSE}$ = 18V | | | | 20 | nA |
| | Internal Bridge Rectifier Reverse Breakdown Voltage | $I_{REVERSE}$ = 1μA | | $V_{SHUNT}$ | 30 | | V |
| $V_{OUT}$ | Regulated Output Voltage | 1.8V Output Selected | | | | | |
| | | Sleep Threshold | ● | | 1.812 | 1.890 | V |
| | | Wake-Up Threshold | ● | 1.710 | 1.788 | | V |
| | | 2.5V Output Selected | | | | | |
| | | Sleep Threshold | ● | | 2.512 | 2.575 | V |
| | | Wake-Up Threshold | ● | 2.425 | 2.488 | | V |
| | | 3.3V Output Selected | | | | | |
| | | Sleep Threshold | ● | | 3.312 | 3.399 | V |
| | | Wake-Up Threshold | ● | 3.201 | 3.288 | | V |
| | | 3.6V Output Selected | | | | | |
| | | Sleep Threshold | ● | | 3.612 | 3.708 | V |
| | | Wake-Up Threshold | ● | 3.492 | 3.588 | | V |
| | PGOOD Falling Threshold | As a Percentage of the Selected $V_{OUT}$ | | 83 | 92 | | % |
| $I_{VOUT}$ | Output Quiescent Current | $V_{OUT}$ = 3.6V | | | 89 | 150 | nA |
| $I_{PEAK}$ | Buck Peak Switch Current | | | 200 | 260 | 350 | mA |
| $I_{BUCK}$ | Available Buck Output Current | | | 100 | | | mA |
| $R_P$ | Buck PMOS Switch On-Resistance | | | | 1.1 | | Ω |
| $R_N$ | Buck NMOS Switch On-Resistance | | | | 1.3 | | Ω |
| | Max Buck Duty Cycle | | ● | 100 | | | % |
| $V_{IH(D0, D1)}$ | D0/D1 Input High Voltage | | ● | 1.2 | | | V |
| $V_{IL(D0, D1)}$ | D0/D1 Input Low Voltage | | ● | | | 0.4 | V |
| $I_{IH(D0, D1)}$ | D0/D1 Input High Current | | | | | 10 | nA |
| $I_{IL(D0, D1)}$ | D0/D1 Input Low Current | | | | | 10 | nA |

## ELECTRICAL CHARACTERISTICS

**Note 1:** Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime.

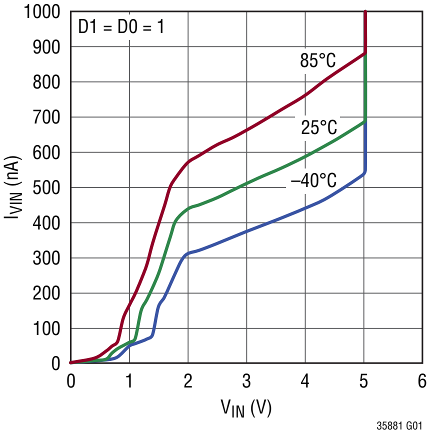
**Note 2:** The LTC3588-1 is tested under pulsed load conditions such that $T_J \approx T_A$. The LTC3588E-1 is guaranteed to meet specifications from 0°C to 85°C junction temperature. Specifications over the –40°C to 125°C operating junction temperature range are assured by design, characterization, and correlation with statistical process controls. The LTC3588I-1 is guaranteed over the full –40°C to 125°C operating junction temperature range. Note that the maximum ambient temperature consistent with these specifications is determined by specific operating conditions in conjunction with board layout, the rated package thermal impedance and other environmental factors.

**Note 3:** The junction temperature ($T_J$, in °C) is calculated from the ambient temperature ($T_A$, in °C) and power dissipation ($P_D$, in Watts) according to the formula: $T_J = T_A + (P_D \bullet \theta_{JA})$, where $\theta_{JA}$ (in °C/W) is the package thermal impedance.

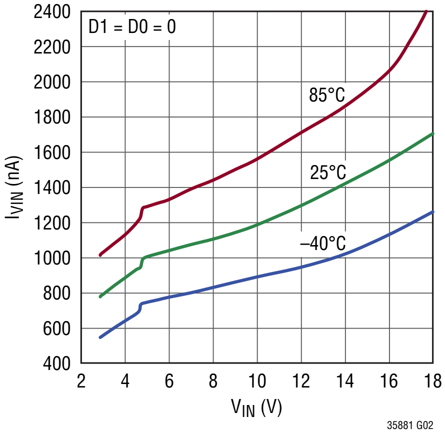
**Note 4:** Dynamic supply current is higher due to gate charge being delivered at the switching frequency.

## TYPICAL PERFORMANCE CHARACTERISTICS

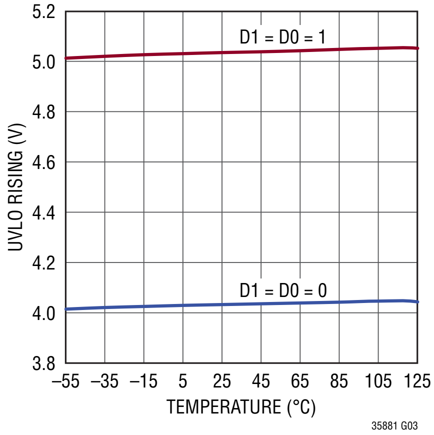
**$I_{VIN}$ in UVLO vs $V_{IN}$**



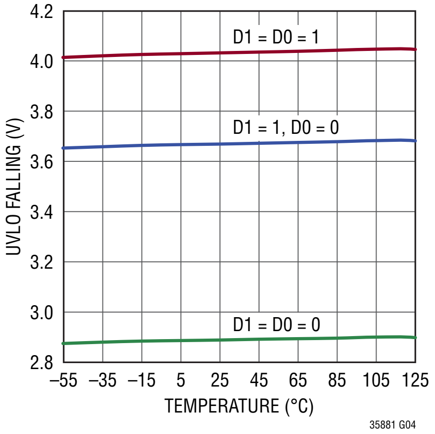
**$I_{VIN}$ in Sleep vs $V_{IN}$**



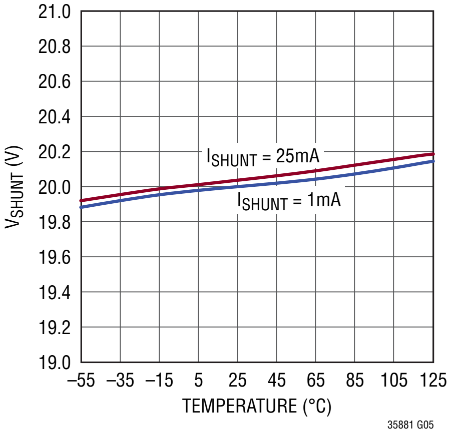
**UVLO Rising vs Temperature**



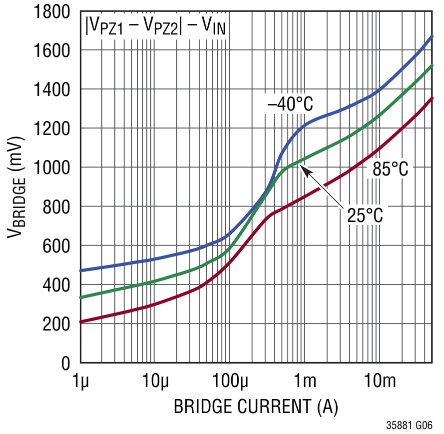
**UVLO Falling vs Temperature**



**$V_{SHUNT}$ vs Temperature**

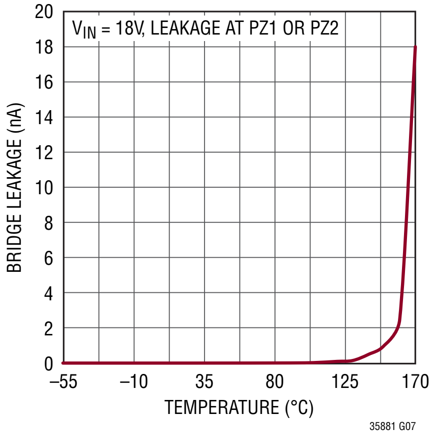


**Total Bridge Rectifier Drop vs Bridge Current**

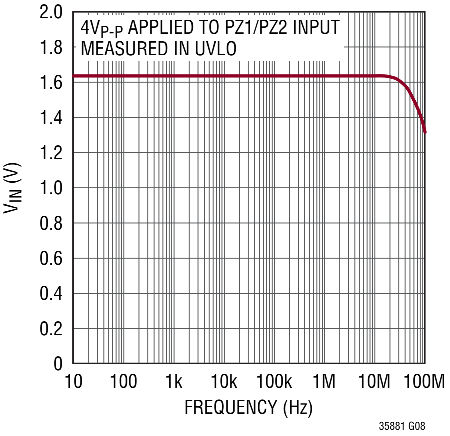


## TYPICAL PERFORMANCE CHARACTERISTICS

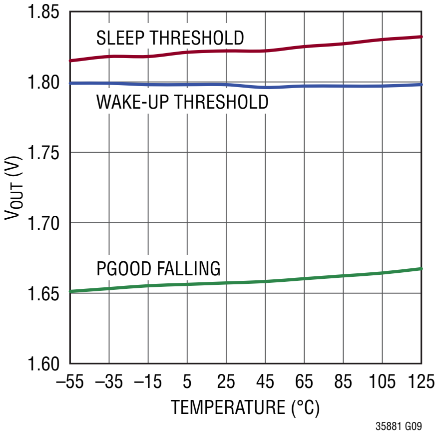
**Bridge Leakage vs Temperature**



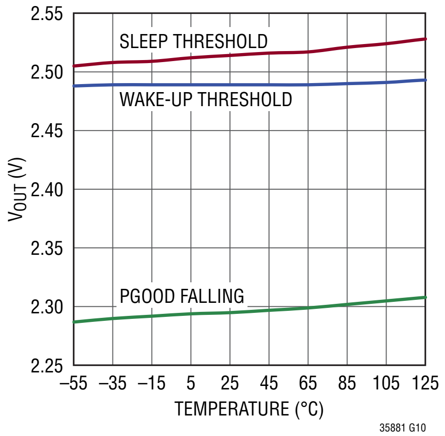
**Bridge Frequency Response**



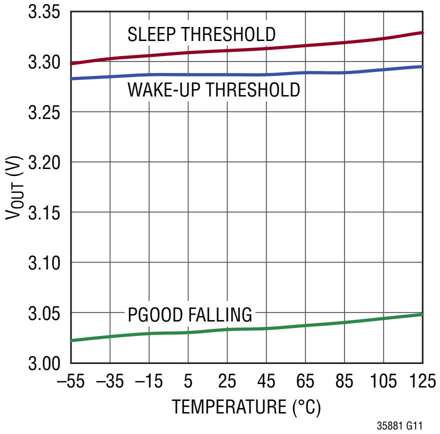
**1.8V Output vs Temperature**



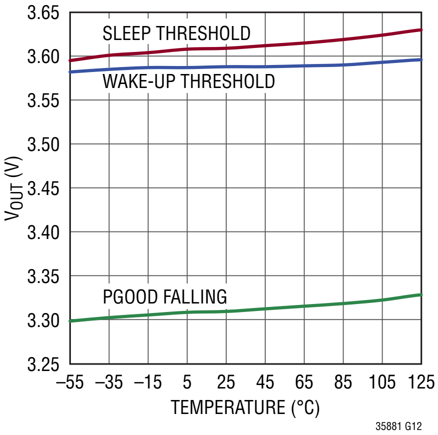
**2.5V Output vs Temperature**



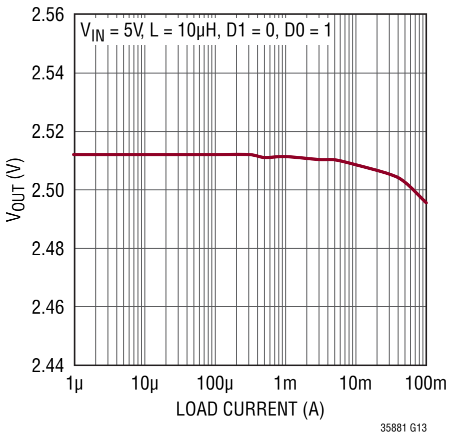
**3.3V Output vs Temperature**



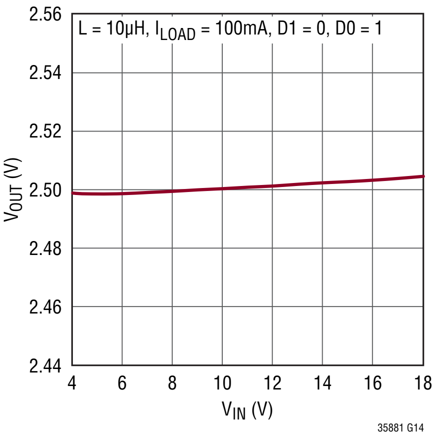
**3.6V Output vs Temperature**



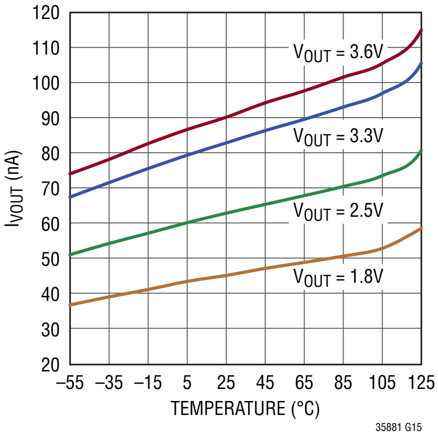
**$V_{OUT}$ Load Regulation**



**$V_{OUT}$ Line Regulation**

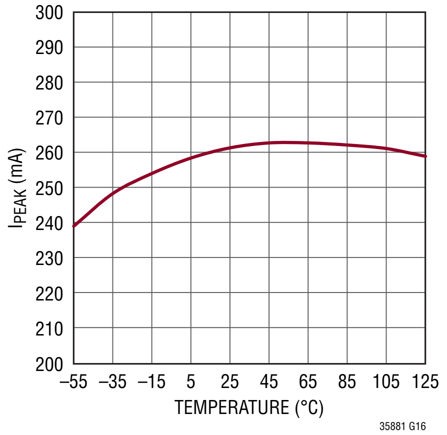


**$I_{VOUT}$ vs Temperature**

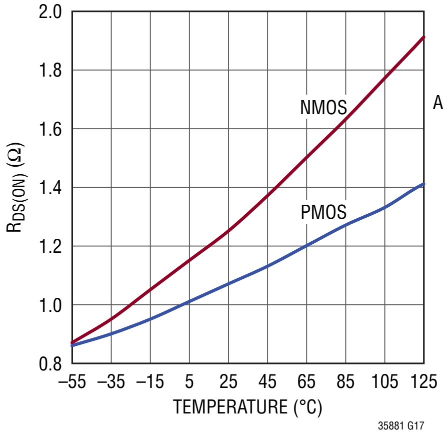


## TYPICAL PERFORMANCE CHARACTERISTICS

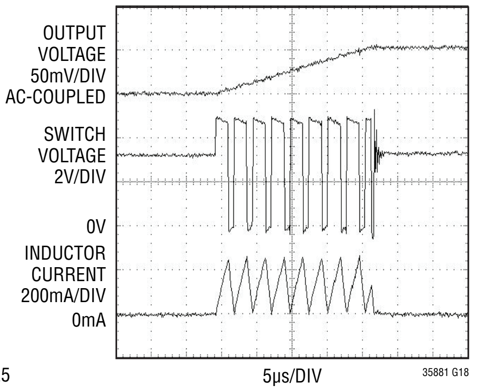
### $I_{PEAK}$ vs Temperature



### $R_{DS(ON)}$ of PMOS/NMOS vs Temperature

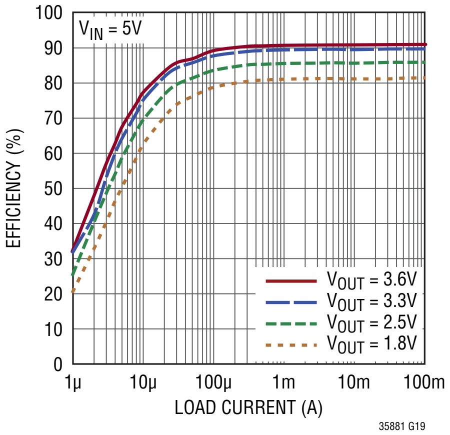


### Operating Waveforms

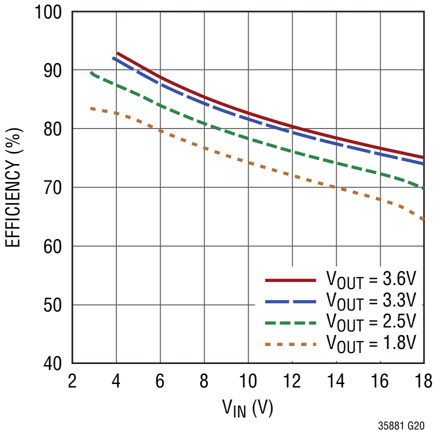


$V_{IN}$ = 5V, $V_{OUT}$ = 3.3V
$I_{LOAD}$ = 1mA
L = 10μH, $C_{OUT}$ = 47μF

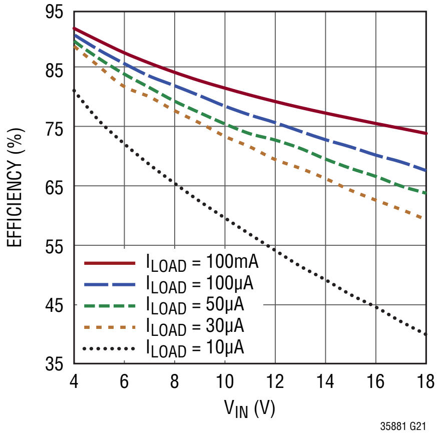
### Efficiency vs $I_{LOAD}$, L = 10μH



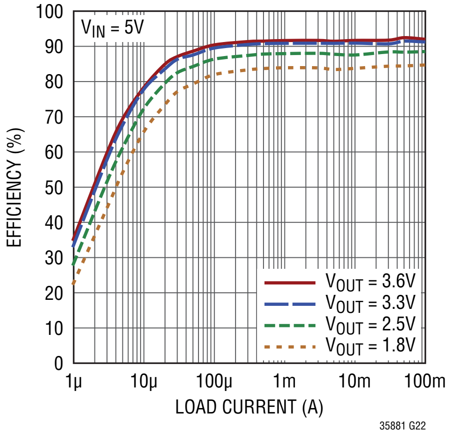
### Efficiency vs $V_{IN}$ for $I_{LOAD}$ = 100mA, L = 10μH



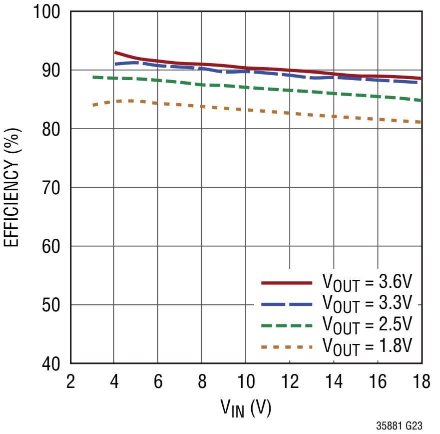
### Efficiency vs $V_{IN}$ for $V_{OUT}$ = 3.3V, L = 10μH



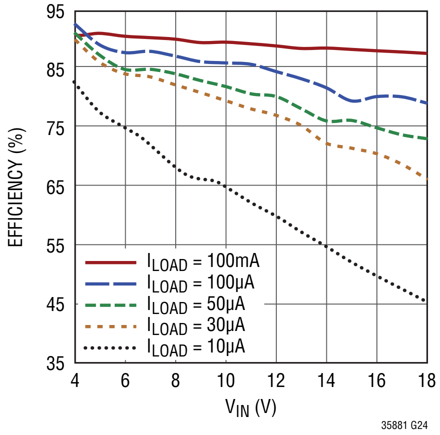
### Efficiency vs $I_{LOAD}$, L = 100μH



### Efficiency vs $V_{IN}$ for $I_{LOAD}$ = 100mA, L = 100μH



### Efficiency vs $V_{IN}$ for $V_{OUT}$ = 3.3V, L = 100μH



## PIN FUNCTIONS

**PZ1 (Pin 1):** Input connection for piezoelectric element or other AC source (used in conjunction with PZ2).

**PZ2 (Pin 2):** Input connection for piezoelectric element or other AC source (used in conjunction with PZ1).

**CAP (Pin 3):** Internal rail referenced to $V_{IN}$ to serve as gate drive for buck PMOS switch. A 1µF capacitor should be connected between CAP and $V_{IN}$. This pin is not intended for use as an external system rail.

**$V_{IN}$ (Pin 4):** Rectified Input Voltage. A capacitor on this pin serves as an energy reservoir and input supply for the buck regulator. The $V_{IN}$ voltage is internally clamped to a maximum of 20V (typical).

**SW (Pin 5):** Switch Pin for the Buck Switching Regulator. A 10µH or larger inductor should be connected from SW to $V_{OUT}$.

**$V_{OUT}$ (Pin 6):** Sense pin used to monitor the output voltage and adjust it through internal feedback.

**$V_{IN2}$ (Pin 7):** Internal low voltage rail to serve as gate drive for buck NMOS switch. Also serves as a logic high rail for output voltage select bits D0 and D1. A 4.7µF capacitor should be connected from $V_{IN2}$ to GND. This pin is not intended for use as an external system rail.

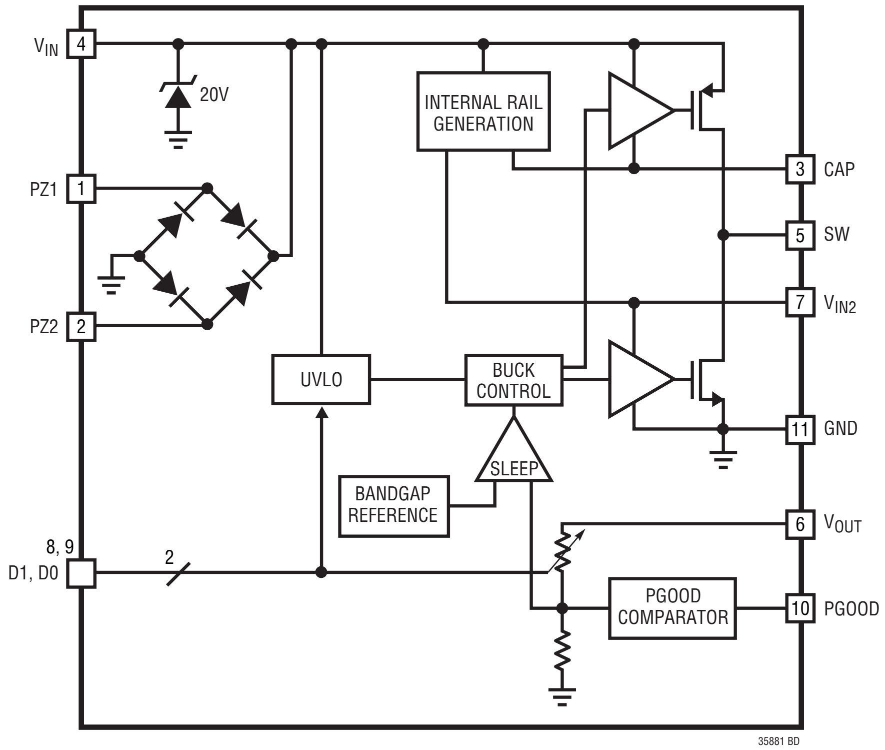
**D1 (Pin 8):** Output Voltage Select Bit. D1 should be tied high to $V_{IN2}$ or low to GND to select desired $V_{OUT}$ (see Table 1).

**D0 (Pin 9):** Output Voltage Select Bit. D0 should be tied high to $V_{IN2}$ or low to GND to select desired $V_{OUT}$ (see Table 1).

**PGOOD (Pin 10):** Power good output is logic high when $V_{OUT}$ is above 92% of the target value. The logic high is referenced to the $V_{OUT}$ rail.

**GND (Exposed Pad Pin 11):** Ground. The Exposed Pad should be connected to a continuous ground plane on the second layer of the printed circuit board by several vias directly under the LTC3588-1.

## BLOCK DIAGRAM



## OPERATION

The LTC3588-1 is an ultralow quiescent current power supply designed specifically for energy harvesting and/or low current step-down applications. The part is designed to interface directly to a piezoelectric or alternative A/C power source, rectify a voltage waveform and store harvested energy on an external capacitor, bleed off any excess power via an internal shunt regulator, and maintain a regulated output voltage by means of a nanopower high efficiency synchronous buck regulator.

### Internal Bridge Rectifier

The LTC3588-1 has an internal full-wave bridge rectifier accessible via the differential PZ1 and PZ2 inputs that rectifies AC inputs such as those from a piezoelectric element. The rectified output is stored on a capacitor at the $V_{IN}$ pin and can be used as an energy reservoir for the buck converter. The low-loss bridge rectifier has a total drop of about 400mV with typical piezo generated currents (~10µA). The bridge is capable of carrying up to 50mA. One side of the bridge can be operated as a single-ended DC input. PZ1 and PZ2 should never be shorted together when the bridge is in use.

### Undervoltage Lockout (UVLO)

When the voltage on $V_{IN}$ rises above the UVLO rising threshold the buck converter is enabled and charge is transferred from the input capacitor to the output capacitor. A wide (~1V) UVLO hysteresis window is employed with a lower threshold approximately 300mV above the selected regulated output voltage to prevent short cycling during buck power-up. When the input capacitor voltage is depleted below the UVLO falling threshold the buck converter is disabled. Extremely low quiescent current (450nA typical) in UVLO allows energy to accumulate on the input capacitor in situations where energy must be harvested from low power sources.

### Internal Rail Generation

Two internal rails, CAP and $V_{IN2}$, are generated from $V_{IN}$ and are used to drive the high side PMOS and low side NMOS of the buck converter, respectively. Additionally the $V_{IN2}$ rail serves as logic high for output voltage select bits D0 and D1. The $V_{IN2}$ rail is regulated at 4.8V above GND while the CAP rail is regulated at 4.8V below $V_{IN}$. These are not intended to be used as external rails. Bypass capacitors are connected to the CAP and $V_{IN2}$ pins to serve as energy reservoirs for driving the buck switches. When $V_{IN}$ is below 4.8V, $V_{IN2}$ is equal to $V_{IN}$ and CAP is held at GND. Figure 1 shows the ideal $V_{IN}$, $V_{IN2}$ and CAP relationship.

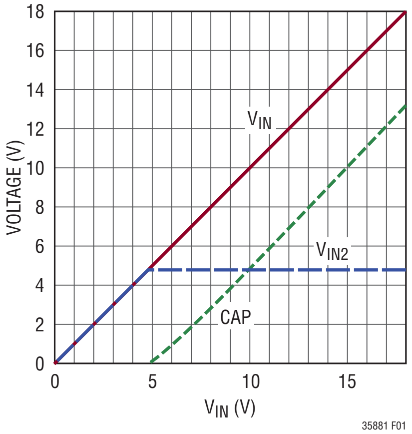


**Figure 1. Ideal $V_{IN}$, $V_{IN2}$ and CAP Relationship**

### Buck Operation

The buck regulator uses a hysteretic voltage algorithm to control the output through internal feedback from the $V_{OUT}$ sense pin. The buck converter charges an output capacitor through an inductor to a value slightly higher than the regulation point. It does this by ramping the inductor current up to 260mA through an internal PMOS switch and then ramping it down to 0mA through an internal NMOS switch. This efficiently delivers energy to the output capacitor. The ramp rate is determined by $V_{IN}$, $V_{OUT}$, and the inductor value. If the input voltage falls below the UVLO falling threshold

## OPERATION

before the output voltage reaches regulation, the buck converter will shut off and will not be turned on until the input voltage again rises above the UVLO rising threshold. During this time the output voltage will be loaded by less than 100nA. When the buck brings the output voltage into regulation the converter enters a low quiescent current sleep state that monitors the output voltage with a sleep comparator. During this operating mode load current is provided by the buck output capacitor. When the output voltage falls below the regulation point the buck regulator wakes up and the cycle repeats. This hysteretic method of providing a regulated output reduces losses associated with FET switching and maintains an output at light loads. The buck delivers a minimum of 100mA of average load current when it is switching.

When the sleep comparator signals that the output has reached the sleep threshold the buck converter may be in the middle of a cycle with current still flowing through the inductor. Normally both synchronous switches would turn off and the current in the inductor would freewheel to zero through the NMOS body diode. The LTC3588-1 keeps the NMOS switch on during this time to prevent the conduction loss that would occur in the diode if the NMOS were off. If the PMOS is on when the sleep comparator trips the NMOS will turn on immediately in order to ramp down the current. If the NMOS is on it will be kept on until the current reaches zero.

Though the quiescent current when the buck is switching is much greater than the sleep quiescent current, it is still a small percentage of the average inductor current which results in high efficiency over most load conditions. The buck operates only when sufficient energy has been accumulated in the input capacitor and the length of time the converter needs to transfer energy to the output is much less than the time it takes to accumulate energy. Thus, the buck operating quiescent current is averaged over a long period of time so that the total average quiescent current is low. This feature accommodates sources that harvest small amounts of ambient energy.

Four selectable voltages are available by tying the output select bits, D0 and D1, to GND or $V_{IN2}$. Table 1 shows the four D0/D1 codes and their corresponding output voltages.

**Table 1. Output Voltage Selection**

| D1 | D0 | $V_{OUT}$ | $V_{OUT}$ QUIESCENT CURRENT ($I_{VOUT}$) |
|---|---|---|---|
| 0 | 0 | 1.8V | 44nA |
| 0 | 1 | 2.5V | 62nA |
| 1 | 0 | 3.3V | 81nA |
| 1 | 1 | 3.6V | 89nA |

The internal feedback network draws a small amount of current from $V_{OUT}$ as listed in Table 1.

### Power Good Comparator

A power good comparator produces a logic high referenced to $V_{OUT}$ on the PGOOD pin the first time the converter reaches the sleep threshold of the programmed $V_{OUT}$, signaling that the output is in regulation. The PGOOD pin will remain high until $V_{OUT}$ falls to 92% of the desired regulation voltage. Several sleep cycles may occur during this time. Additionally, if PGOOD is high and $V_{IN}$ falls below the UVLO falling threshold, PGOOD will remain high until $V_{OUT}$ falls to 92% of the desired regulation point. This allows output energy to be used even if the input is lost. Figure 2 shows the behavior for $V_{OUT}$ = 3.6V and no load. At t = 75s $V_{IN}$ becomes high impedance and is discharged by the quiescent current of the LTC3588-1 and through servicing $V_{OUT}$ which is discharged by its own leakage current. $V_{IN}$ crosses UVLO falling but PGOOD remains high until $V_{OUT}$ decreases to 92% of the desired regulation point. The PGOOD pin is designed to drive a microprocessor or other chip I/O and is not intended to drive higher current loads such as an LED.

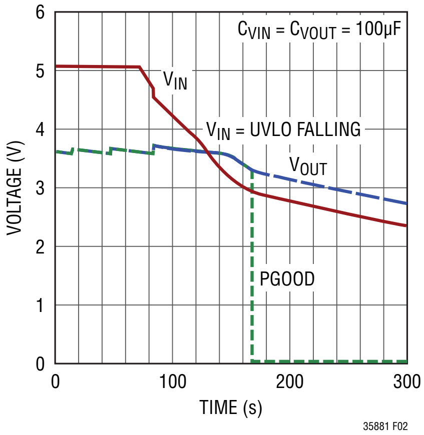


**Figure 2. PGOOD Operation During Transition to UVLO**

## OPERATION

The D0/D1 inputs can be switched while in regulation as shown in Figure 3. If $V_{OUT}$ is programmed to a voltage with a PGOOD falling threshold above the old $V_{OUT}$, PGOOD will transition low until the new regulation point is reached. When $V_{OUT}$ is programmed to a lower voltage, PGOOD will remain high through the transition.

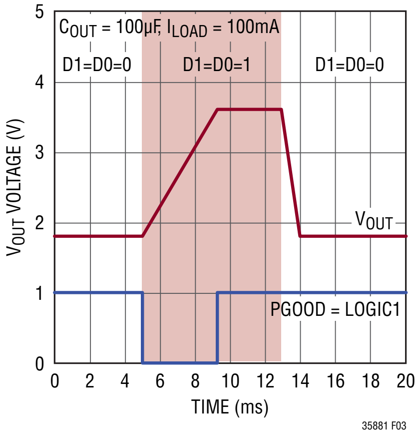


**Figure 3. PGOOD Operation During D0/D1 Transition**

### Energy Storage

Harvested energy can be stored on the input capacitor or the output capacitor. The wide input range takes advantage of the fact that energy storage on a capacitor is proportional to the square of the capacitor voltage. After the output voltage is brought into regulation any excess energy is stored on the input capacitor and its voltage increases. When a load exists at the output the buck can efficiently transfer energy stored at a high voltage to the regulated output. While energy storage at the input utilizes the high voltage at the input, the load current is limited to what the buck converter can supply. If larger loads need to be serviced the output capacitor can be sized to support a larger current for some duration. For example, a current burst could begin when PGOOD goes high and would continuously deplete the output capacitor until PGOOD went low.

## APPLICATIONS INFORMATION

### Introduction

The LTC3588-1 harvests ambient vibrational energy through a piezoelectric element in its primary application. Common piezoelectric elements are PZT (lead zirconate titanate) ceramics, PVDF (polyvinylidene fluoride) polymers, or other composites. Ceramic piezoelectric elements exhibit a piezoelectric effect when the crystal structure of the ceramic is compressed and internal dipole movement produces a voltage. Polymer elements comprised of long-chain molecules produce a voltage when flexed as molecules repel each other. Ceramics are often used under direct pressure while a polymer can be flexed more readily. A wide range of piezoelectric elements are available and produce a variety of open-circuit voltages and short-circuit currents. Typically the open-circuit voltage and short-circuit currents increase with available vibrational energy as shown in Figure 4. Piezoelectric elements can be placed in series or in parallel to achieve desired open-circuit voltages.

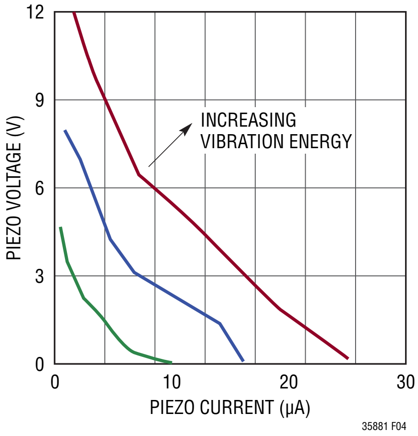


**Figure 4. Typical Piezoelectric Load Lines for Piezo Systems T220-A4-503X**

The LTC3588-1 is well-suited to a piezoelectric energy harvesting application. The 20V input protective shunt can accommodate a variety of piezoelectric elements. The low quiescent current of the LTC3588-1 enables efficient energy accumulation from piezoelectric elements which can have short-circuit currents on the order of tens of microamps. Piezoelectric elements can be obtained from manufacturers listed in Table 2.

**Table 2. Piezoelectric Element Manufacturers**

| | |
|---|---|
| Advanced Cerametrics | www.advancedcerametrics.com |
| Piezo Systems | www.piezo.com |
| Measurement Specialties | www.meas-spec.com |
| PI (Physik Instrumente) | www.pi-usa.us |
| MIDE Technology Corporation | www.mide.com |
| Morgan Technical Ceramics | www.morganelectroceramics.com |

The LTC3588-1 will gather energy and convert it to a useable output voltage to power microprocessors, wireless sensors, and wireless transmission components. Such a wireless sensor application may require much more peak power than a piezoelectric element can produce. However, the LTC3588-1 accumulates energy over a long period of time to enable efficient use for short power bursts. For continuous operation, these bursts must occur with a low duty cycle such that the total output energy during the burst does not exceed the average source power integrated over an energy accumulation cycle. For piezoelectric inputs the time between cycles could be minutes, hours, or longer depending on the selected capacitor values and the nature of the vibration source.

## APPLICATIONS INFORMATION

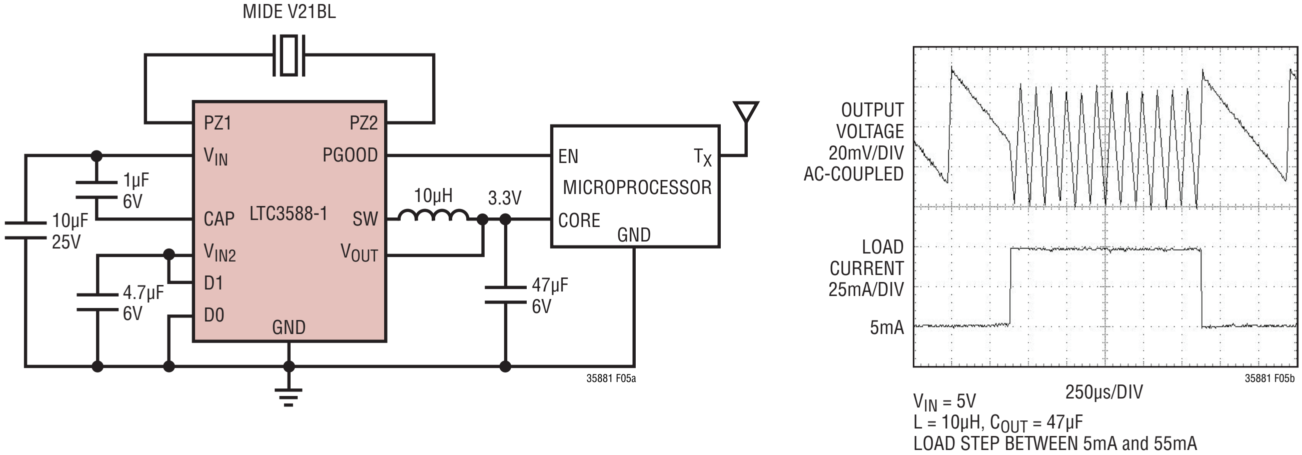


**Figure 5. 3.3V Piezoelectric Energy Harvester Powering a Microprocessor with a Wireless Transmitter and 50mA Load Step Response**

### PGOOD Signal

The PGOOD signal can be used to enable a sleeping microprocessor or other circuitry when $V_{OUT}$ reaches regulation, as shown in Figure 5. Typically $V_{IN}$ will be somewhere between the UVLO thresholds at this time and a load could only be supported by the output capacitor. Alternatively, waiting a period of time after PGOOD goes high would let the input capacitor accumulate more energy allowing load current to be maintained longer as the buck efficiently transfers that energy to the output. While active, a microprocessor may draw a small load when operating sensors, and then draw a large load to transmit data. Figure 5 shows the LTC3588-1 responding smoothly to such a load step.

### Input and Output Capacitor Selection

The input and output capacitors should be selected based on the energy needs and load requirements of the application. In every case the $V_{IN}$ capacitor should be rated to withstand the highest voltage ever present at $V_{IN}$. For 100mA or smaller loads, storing energy at the input takes advantage of the high voltage input since the buck can deliver 100mA average load current efficiently to the output. The input capacitor should then be sized to store enough energy to provide output power for the length of time required. This may involve using a large capacitor, letting $V_{IN}$ charge to a high voltage, or both. Enough energy should be stored on the input so that the buck does not reach the UVLO falling threshold which would halt energy transfer to the output. In general:

$$P_{LOAD}t_{LOAD} = \frac{1}{2}\eta C_{IN}\left(V_{IN}^{2} - V_{UVLOFALLING}^{2}\right)$$

$$V_{UVLOFALLING} \le V_{IN} \le V_{SHUNT}$$

The above equation can be used to size the input capacitor to meet the power requirements of the output for the desired duration. Here $\eta$ is the average efficiency of the buck converter over the input range and $V_{IN}$ is the input voltage when the buck begins to switch. This equation may overestimate the input capacitor necessary since load current can deplete the output capacitor all the way to the lower PGOOD threshold. It also assumes that the input source charging has a negligible effect during this time.

The duration for which the regulator sleeps depends on the load current and the size of the output capacitor. The sleep time decreases as the load current increases and/or as the output capacitor decreases. The DC sleep hysteresis window is ±12mV around the programmed output voltage. Ideally this means that the sleep time is determined by the following equation:

$$t_{SLEEP} = C_{OUT}\frac{24mV}{I_{LOAD}}$$

## APPLICATIONS INFORMATION

This is true for output capacitors on the order of 100µF or larger, but as the output capacitor decreases towards 10µF delays in the internal sleep comparator along with the load current may result in the $V_{OUT}$ voltage slewing past the ±12mV thresholds. This will lengthen the sleep time and increase $V_{OUT}$ ripple. A capacitor less than 10µF is not recommended as $V_{OUT}$ ripple could increase to an undesirable level.

If transient load currents above 100mA are required then a larger capacitor can be used at the output. This capacitor will be continuously discharged during a load condition and the capacitor can be sized for an acceptable drop in $V_{OUT}$:

$$C_{OUT} = (I_{LOAD} - I_{BUCK})\frac{t_{LOAD}}{V_{OUT}^{+} - V_{OUT}^{-}}$$

Here $V_{OUT}^{+}$ is the value of $V_{OUT}$ when PGOOD goes high and $V_{OUT}^{-}$ is the desired lower limit of $V_{OUT}$. $I_{BUCK}$ is the average current being delivered from the buck converter, typically $I_{PEAK}/2$.

A standard surface mount ceramic capacitor can be used for $C_{OUT}$, though some applications may be better suited to a low leakage aluminum electrolytic capacitor or a supercapacitor. These capacitors can be obtained from manufacturers such as Vishay, Illinois Capacitor, AVX, or CAP-XX.

### Inductor

The buck is optimized to work with an inductor in the range of 10µH to 22µH, although inductor values outside this range may yield benefits in some applications. For typical applications, a value of 10µH is recommended. A larger inductor will benefit high voltage applications by increasing the on-time of the PMOS switch and improving efficiency by reducing gate charge loss. Choose an inductor with a DC current rating greater than 350mA. The DCR of the inductor can have an impact on efficiency as it is a source of loss. Trade-offs between price, size, and DCR should be evaluated. Table 3 lists several inductors that work well with the LTC3588-1.

**Table 3. Recommended Inductors for LTC3588-1**

| INDUCTOR TYPE | L (µH) | MAX $I_{DC}$ (mA) | MAX DCR (Ω) | SIZE in mm (L × W × H) | MANUFACTURER |
|---|---|---|---|---|---|
| CDRH2D18/LDNP | 10 | 430 | 0.180 | 3 × 3 × 2 | Sumida |
| 107AS-100M | 10 | 650 | 0.145 | 2.8 × 3 × 1.8 | Toko |
| EPL3015-103ML | 10 | 350 | 0.301 | 2.8 × 3 × 1.5 | Coilcraft |
| MLP3225s100L | 10 | 1000 | 0.130 | 3.2 × 2.5 × 1.0 | TDK |
| XLP2010-163ML | 10 | 490 | 0.611 | 2.0 × 1.9 × 1.0 | Coilcraft |
| SLF7045T | 100 | 500 | 0.250 | 7.0 × 7.0 × 4.5 | TDK |

### $V_{IN2}$ and CAP Capacitors

A 1µF capacitor should be connected between $V_{IN}$ and CAP and a 4.7µF capacitor should be connected between $V_{IN2}$ and GND. These capacitors hold up the internal rails during buck switching and compensate the internal rail generation circuits. In applications where the input source is limited to less than 6V, the CAP pin can be tied to GND and the $V_{IN2}$ pin can be tied to $V_{IN}$ as shown in Figure 6. An optional 5.6V Zener diode can be connected to $V_{IN}$ to clamp $V_{IN}$ in this scenario. The leakage of the Zener diode below its Zener voltage should be considered as it may be comparable to the quiescent current of the LTC3588-1. This circuit does not require the capacitors on $V_{IN2}$ and CAP, saving components and allowing a lower voltage rating for the single $V_{IN}$ capacitor.

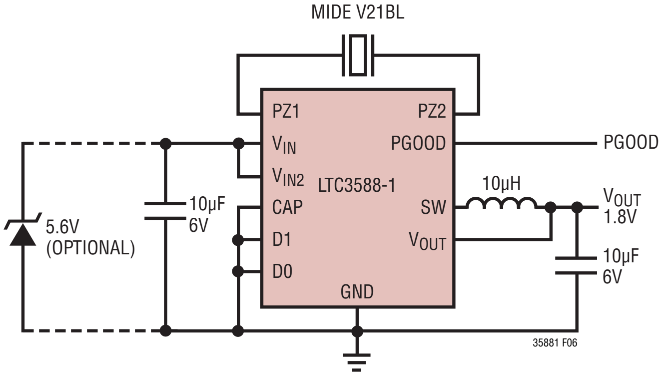


**Figure 6. Smallest Solution Size 1.8V Low Voltage Input Piezoelectric Power Supply**

## APPLICATIONS INFORMATION

### Additional Applications with Piezo Inputs

The versatile LTC3588-1 can be used in a variety of configurations. Figure 7 shows a single piezo source powering two LTC3588-1s simultaneously, providing capability for multiple rail systems. This setup features automatic supply sequencing as the LTC3588-1 with the lower voltage output (i.e. lower UVLO rising threshold) will come up first. As the piezo provides input power both $V_{IN}$ rails will initially come up together, but when one output starts drawing power, only its corresponding $V_{IN}$ will fall as the bridges of each LTC3588-1 provide isolation. Input piezo energy will then be directed to this lower voltage capacitor until both $V_{IN}$ rails are again equal. This configuration is expandable to any number of LTC3588-1s powered by a single piezo as long as the piezo can support the sum total of the quiescent currents from each LTC3588-1.

A piezo powered LTC3588-1 can also be used in concert with a battery connected to $V_{IN}$ to supplement the system if ambient vibrational energy ceases as shown in Figure 8. A blocking diode placed in series with the battery to $V_{IN}$ prevents reverse current in the battery if the piezo source charges $V_{IN}$ past the battery voltage. A 9V battery is shown, but any stack of batteries of a given chemistry can be used as long as the battery stack voltage does not exceed 18V. In this setup the presence of the piezo energy harvester can greatly increase the life of the battery. If the piezo source is removed the LTC3588-1 can serve as a standalone nanopower buck converter. In this case the bridge is unused and the blocking diode is unnecessary.

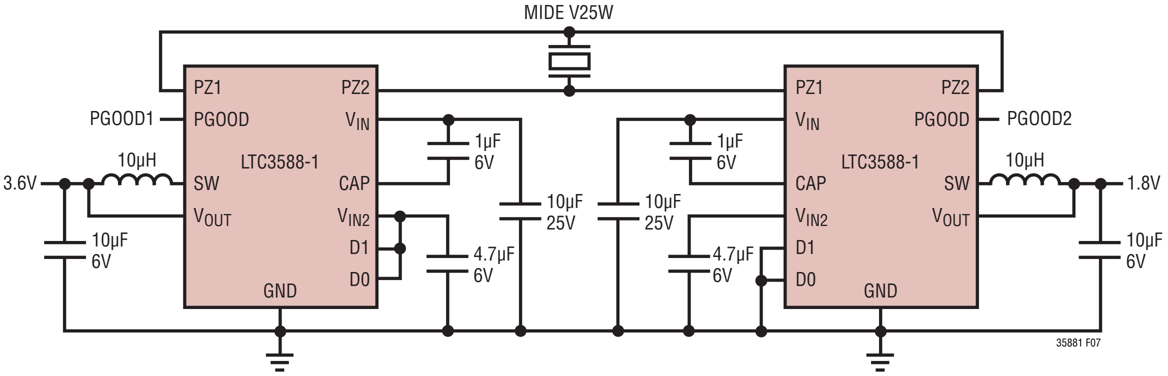


**Figure 7. Dual Rail Power Supply with Single Piezo and Automatic Supply Sequencing**

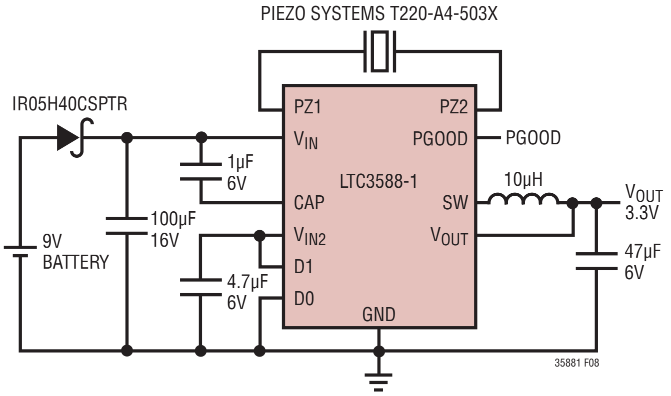
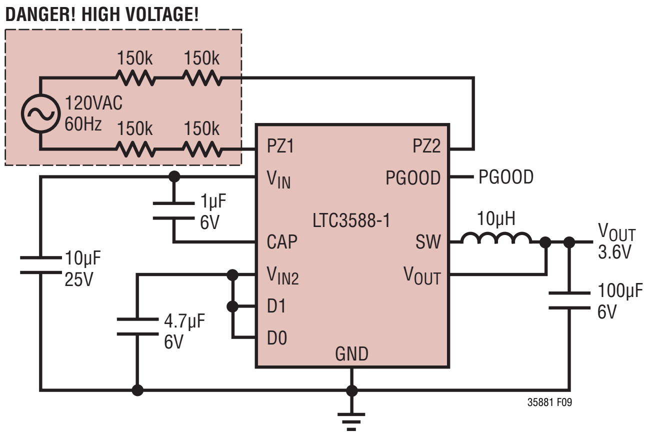


**Figure 8. Piezo Energy Harvester with Battery Backup**

## APPLICATIONS INFORMATION



**DANGEROUS AND LETHAL POTENTIALS ARE PRESENT IN OFFLINE CIRCUITS! BEFORE PROCEEDING ANY FURTHER, THE READER IS WARNED THAT CAUTION MUST BE USED IN THE CONSTRUCTION, TESTING AND USE OF OFFLINE CIRCUITS. EXTREME CAUTION MUST BE USED IN WORKING WITH AND MAKING CONNECTIONS TO THESE CIRCUITS. REPEAT: OFFLINE CIRCUITS CONTAIN DANGEROUS, AC LINE-CONNECTED HIGH VOLTAGE POTENTIALS. USE CAUTION. ALL TESTING PERFORMED ON AN OFFLINE CIRCUIT MUST BE DONE WITH AN ISOLATION TRANSFORMER CONNECTED BETWEEN THE OFFLINE CIRCUIT'S INPUT AND THE AC LINE. USERS AND CONSTRUCTORS OF OFFLINE CIRCUITS MUST OBSERVE THIS PRECAUTION WHEN CONNECTING TEST EQUIPMENT TO THE CIRCUIT TO AVOID ELECTRIC SHOCK. REPEAT: AN ISOLATION TRANSFORMER MUST BE CONNECTED BETWEEN THE CIRCUIT INPUT AND THE AC LINE IF ANY TEST EQUIPMENT IS TO BE CONNECTED.**

**Figure 9. AC Line Powered 3.6V Buck Regulator with Large Output Capacitor to Support Heavy Loads**

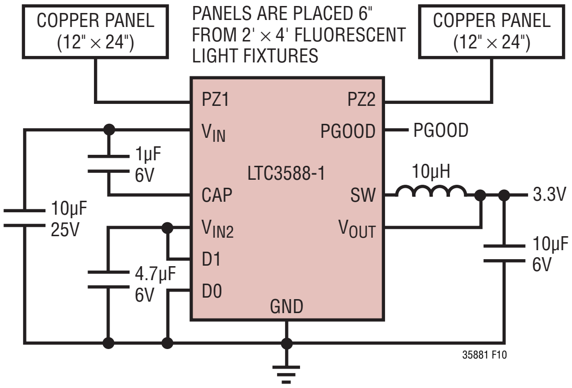


**Figure 10. Electric Field Energy Harvester**

### Alternate Power Sources

The LTC3588-1 is not limited to use with piezoelectric elements but can accommodate a wide variety of input sources depending on the type of ambient energy available. Figure 9 shows the LTC3588-1 internal bridge rectifier connected to the AC line in series with four 150k current limiting resistors. This is a high voltage application and minimum spacing between the line, neutral, and any high voltage components should be maintained per the applicable UL specification. For general off-line applications refer to UL regulation 1012.

Figure 10 shows an application where copper panels are placed near a standard fluorescent room light to capacitively harvest energy from the electric field around the light. The frequency of the emission will be 120Hz for magnetic ballasts but could be higher if the light uses electronic ballast. The LTC3588-1 bridge rectifier can handle a wide range of input frequencies.

The LTC3588-1 can also be configured for use with DC sources such as a solar panel or thermal couple as shown in Figures 11 and 12 by connecting them to one of the PZ1/PZ2 inputs. Connecting the two sources in this way prevents reverse current from flowing in each element. Current limiting resistors should be used to protect the PZ1 or PZ2 pins. This can be combined with a battery backup connected to $V_{IN}$ with a blocking diode.

## APPLICATIONS INFORMATION

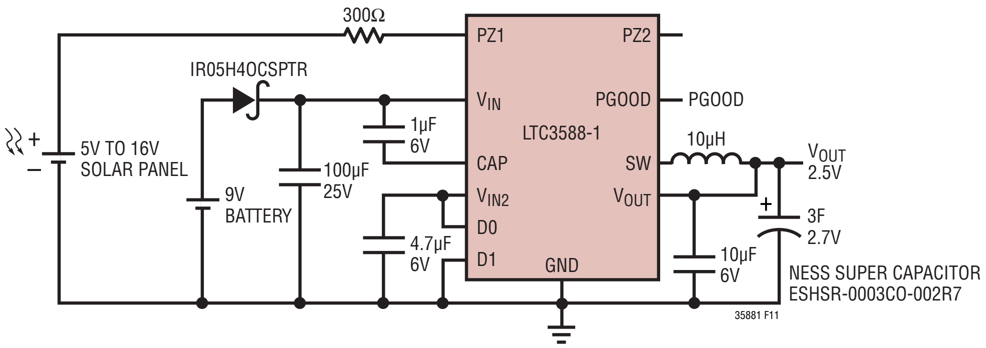


**Figure 11. 5V to 16V Solar-Powered 2.5V Supply with Supercapacitor for Increased Output Energy Storage and Battery Backup**

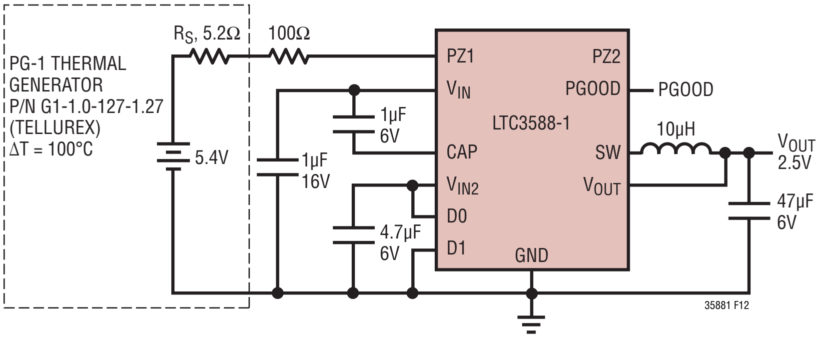
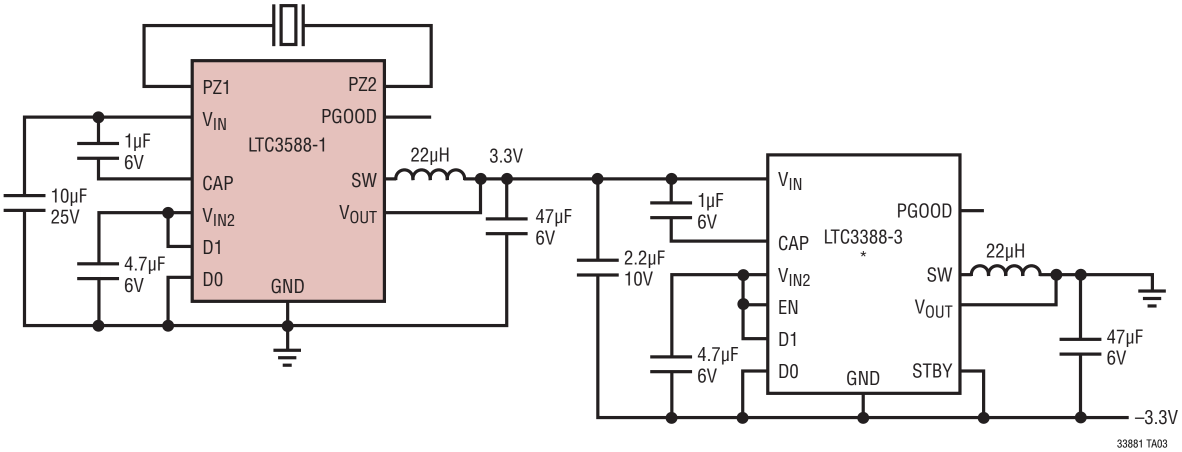


**Figure 12. Thermoelectric Energy Harvester**



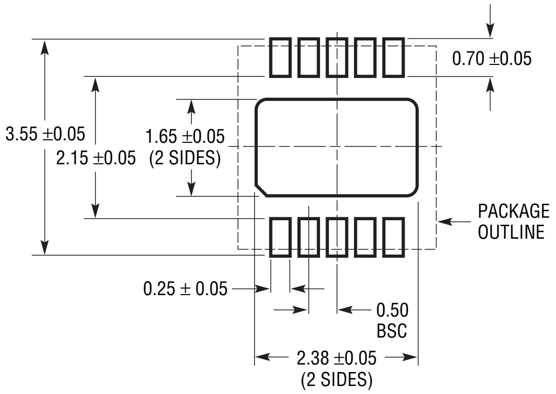
* EXPOSED PAD MUST BE ELECTRICALLY ISOLATED FROM SYSTEM GROUND AND CONNECTED TO THE –3.3V RAIL.

**Figure 13. Piezoelectric Energy Harvester with ±3.3V Outputs**

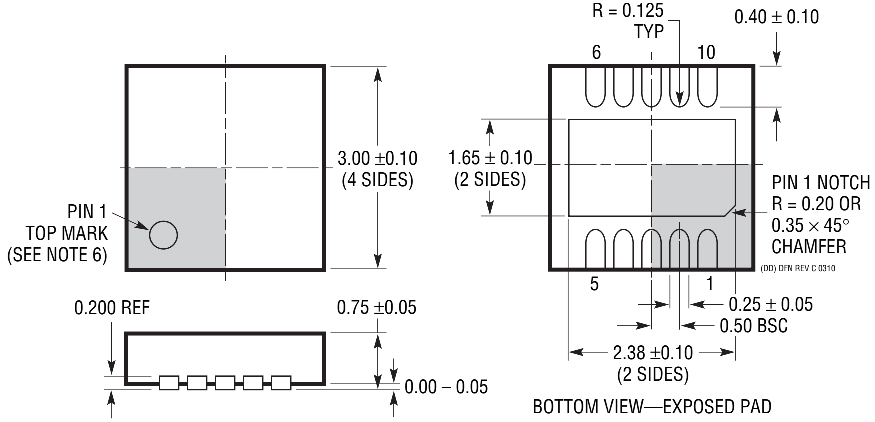
# PACKAGE DESCRIPTION

**Please refer to http://www.linear.com/designtools/packaging/ for the most recent package drawings.**

**DD Package**
**10-Lead Plastic DFN (3mm × 3mm)**
(Reference LTC DWG # 05-08-1699 Rev C)



**RECOMMENDED** SOLDER PAD PITCH AND DIMENSIONS



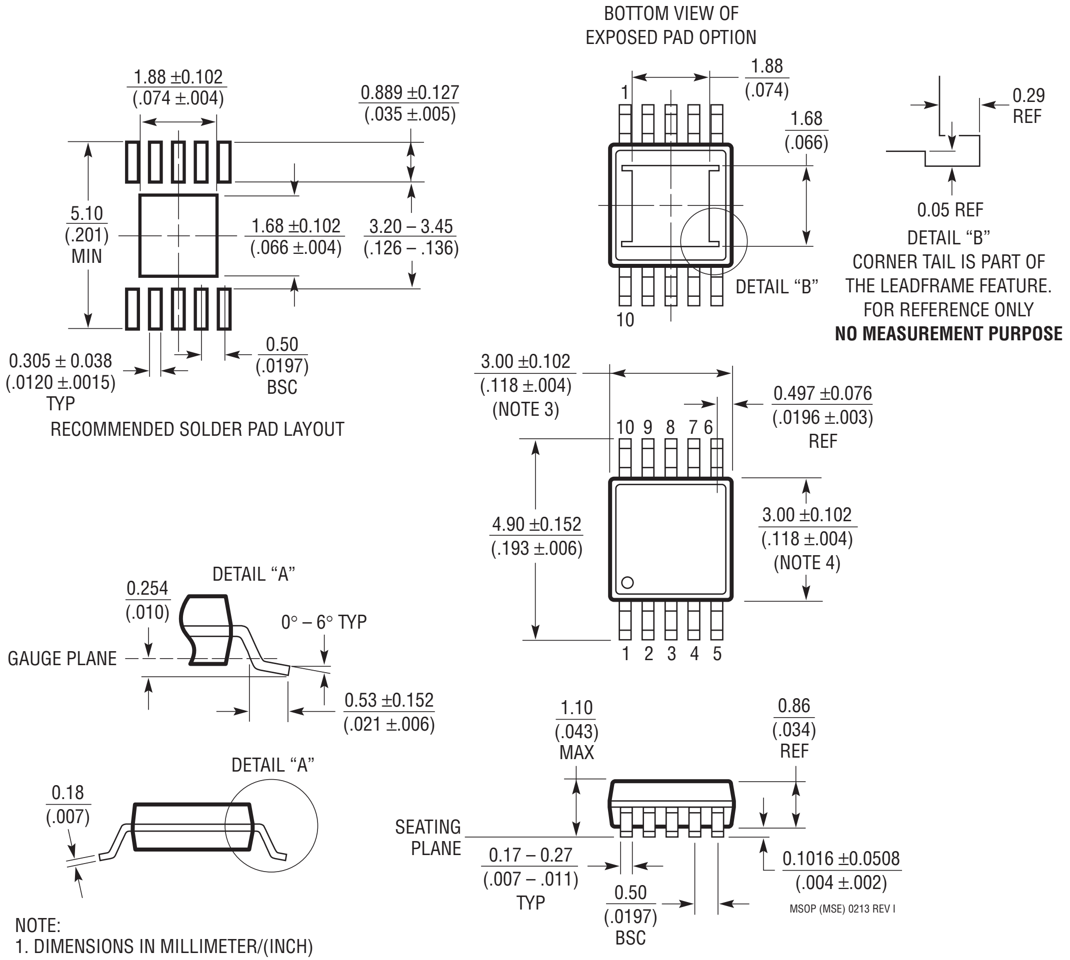
BOTTOM VIEW—EXPOSED PAD

NOTE:
1. DRAWING TO BE MADE A JEDEC PACKAGE OUTLINE M0-229 VARIATION OF (WEED-2). CHECK THE LTC WEBSITE DATA SHEET FOR CURRENT STATUS OF VARIATION ASSIGNMENT
2. DRAWING NOT TO SCALE
3. ALL DIMENSIONS ARE IN MILLIMETERS
4. DIMENSIONS OF EXPOSED PAD ON BOTTOM OF PACKAGE DO NOT INCLUDE MOLD FLASH. MOLD FLASH, IF PRESENT, SHALL NOT EXCEED 0.15mm ON ANY SIDE
5. EXPOSED PAD SHALL BE SOLDER PLATED
6. SHADED AREA IS ONLY A REFERENCE FOR PIN 1 LOCATION ON THE TOP AND BOTTOM OF PACKAGE

## PACKAGE DESCRIPTION

**Please refer to http://www.linear.com/designtools/packaging/ for the most recent package drawings.**

**MSE Package**
**10-Lead Plastic MSOP, Exposed Die Pad**
(Reference LTC DWG # 05-08-1664 Rev I)



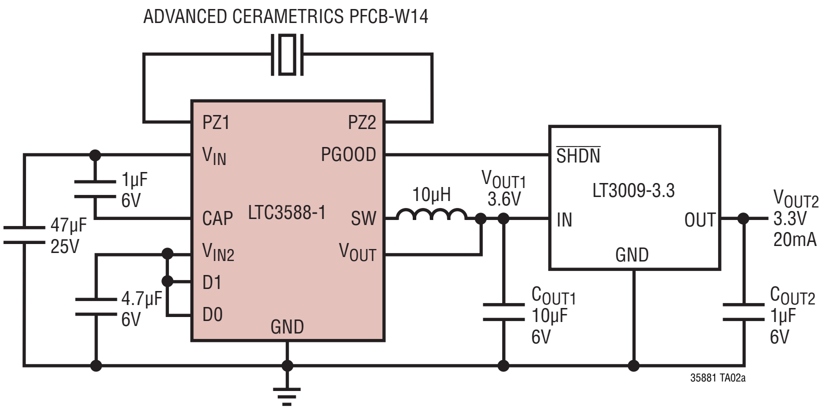
NOTE:
1. DIMENSIONS IN MILLIMETER/(INCH)
2. DRAWING NOT TO SCALE
3. DIMENSION DOES NOT INCLUDE MOLD FLASH, PROTRUSIONS OR GATE BURRS. MOLD FLASH, PROTRUSIONS OR GATE BURRS SHALL NOT EXCEED 0.152mm (.006") PER SIDE
4. DIMENSION DOES NOT INCLUDE INTERLEAD FLASH OR PROTRUSIONS. INTERLEAD FLASH OR PROTRUSIONS SHALL NOT EXCEED 0.152mm (.006") PER SIDE
5. LEAD COPLANARITY (BOTTOM OF LEADS AFTER FORMING) SHALL BE 0.102mm (.004") MAX
6. EXPOSED PAD DIMENSION DOES INCLUDE MOLD FLASH. MOLD FLASH ON E-PAD SHALL NOT EXCEED 0.254mm (.010") PER SIDE.

## REVISION HISTORY

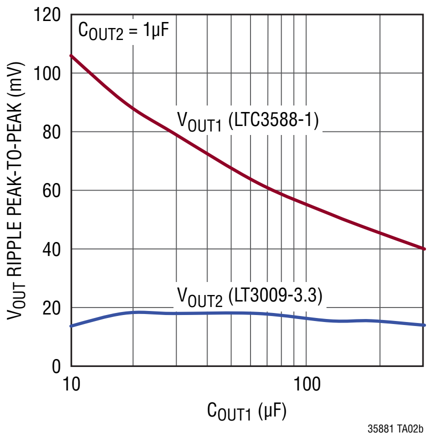
| REV | DATE | DESCRIPTION | PAGE NUMBER |
|---|---|---|---|
| A | 9/10 | Updated/added part number on the Piezoelectric Transducer on the front and back page applications, and Figures 5, 6 and 7 | 1, 12, 13, 14, 20 |
| | | Updated Temperature Range in Order Information | 2 |
| | | Changed $T_J$ = 25°C to $T_A$ = 25°C and $I_{LOAD}$ to $I_{BUCK}$ in Electrical Characteristics | 3 |
| | | Updated Notes 2, 3 and 4 | 4 |
| | | Updated G21 in Typical Performance Characteristics | 6 |
| | | Added Figure 13 | 16 |
| | | Updated Related Parts | 20 |
| B | 7/14 | Clarified title and Description | 1 |
| | | Clarified x-axis label on Figure 1 | 8 |
| | | Clarified Figure 8 | 14 |
| | | Clarified Related Parts list | 20 |
| C | 8/15 | Modified $C_{OUT}$ Equation | 13 |

# TYPICAL APPLICATION

**Piezoelectric 3.3V Power Supply with LDO Post Regulator for Reduced Output Ripple**



**Peak-to-Peak Output Ripple vs $C_{OUT1}$**



# RELATED PARTS

| PART NUMBER | DESCRIPTION | COMMENTS |
|---|---|---|
| LT1389 | Nanopower Precision Shunt Voltage Reference | 800nA Operating Current, 1.25V/2.5V/4.096V |
| LTC1540 | Nanopower Comparator with Reference | 0.3µA $I_Q$, Drives 0.01µF, Adjustable Hysteresis, 2V to 11V Input Range |
| LT3009 | 3µA $I_Q$, 20mA Low Dropout Linear Regulator | Low 3µA $I_Q$, 1.6V to 20V Range, 20mA Output Current |
| LTC3388-1/ LTC3388-3 | 20V High Efficiency Nanopower Step-Down Regulator | 860nA $I_Q$ in Sleep, 2.7V to 20V Input, $V_{OUT}$: 1.2V to 5.0V, Enable and Standby Pins |
| LTC3588-2 | Nanopower Energy Harvesting Power Supply | <1µA $I_Q$ in Regulation, UVLO Rising = 16V, UVLO Falling = 14V, $V_{OUT}$ = 3.45V, 4.1V, 4.5V 5.0V |
| LT3652 | Power Tracking 2A Battery Charger for Solar Power | MPPT for Solar, 4.95V to 32V, Up to 2A Charge Current |
| LT3970 | 40V, 350mA Step-Down Regulator with 2.5µA $I_Q$ | Integrated Boost and Catch Diodes, 4.2V to 40V Operating Range |
| LT3971 | 38V, 1.2A, 2MHz Step-Down Regulator with 2.8µA $I_Q$ | 4.3V to 38V Operating Range, Low Ripple Burst Mode® Operation |
| LT3991 | 55V, 1.2A 2MHz Step-Down Regulator with 2.8µA $I_Q$ | 4.3V to 55V Operating Range, Low Ripple Burst Mode Operation |
| LTC3631 | 45V, 100mA, Synchronous Step-Down Regulator with 12µA $I_Q$ | 4.5V to 45V Operating Range, Overvoltage Lockout Up to 60V |
| LTC3642 | 45V, 50mA, Synchronous Step-Down Regulator with 12µA $I_Q$ | 4.5V to 45V Operating Range, Overvoltage Lockout Up to 60V |
| LTC3330 | Nanopower Buck-Boost DC/DC with Energy Harvesting Battery Life Extender | $V_{IN}$: 2.7V to 20V, BAT: 1.8V to 5.5V, 750nA $I_Q$, 5mm × 5mm QFN-32 Package |
| LTC3331 | Nanopower Buck-Boost DC/DC with Energy Harvesting Battery Charger | $V_{IN}$: 2.7V to 20V, BAT: Up to 4.2V, Shunt Charger, Low Battery Disconnect, 950nA $I_Q$, 5mm × 5mm QFN-32 Package |

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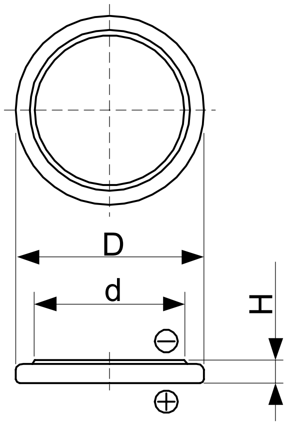
# Anexo VII: *Datasheet* batería ML2430

**FDK**
**Lithium**

# Cell Type ML2430
# Specifications



| | | |
|---|---|---|
| Nominal Capacity[*1] | | 100mAh |
| Nominal Voltage | | 3V |
| Standard Charge/Discharge Current | | 0.5mA |
| Max. Discharge Current | Continuous[*2] | 10mA |
| | Pulse[*3] | 20mA |
| Charge/Discharge Cycle Characteristics | Discharging Depth of 5% | 3000 |
| | Discharging Depth of 20% | 500 |
| Charging Method | Constant Voltage Charge | 3.1±0.15V |
| | Hight Temperature | 2.95±0.15V |
| Temperature Range | | -20℃～60℃ |
| Weight | | 4.1g |
| Dimensions | Diameter(D) | 24.5mm |
| | Height(H) | 3.0mm |
| | d | 20mm |

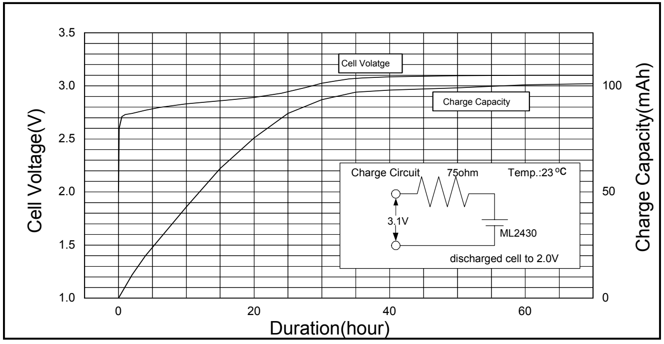
*1 Nominal capacity is determined to an end voltage of 2.0V when the battery is allowed to discharge at a standard current level at 23°C.

*2 Current value is determined so that 50% of the nominal capacity is obtained with an end voltage of 2.0V at 23 °C.

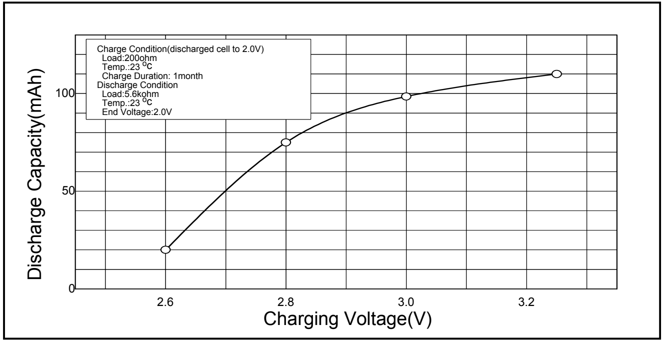
*3 Current value for obtaining 2.0V cell voltage when 15sec. pulse is applied at 50% discharge depth at 23 °C.

## Typical Characteristics

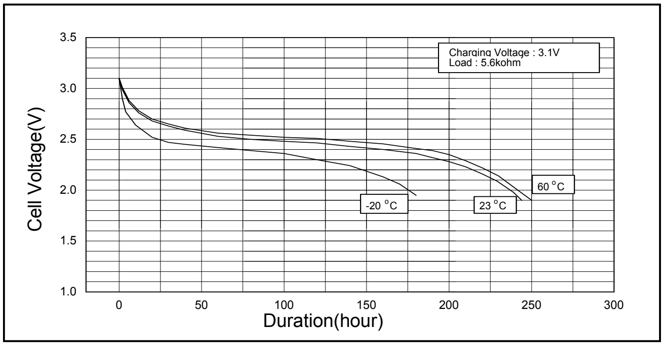
### Charge Characteristics of ML2430



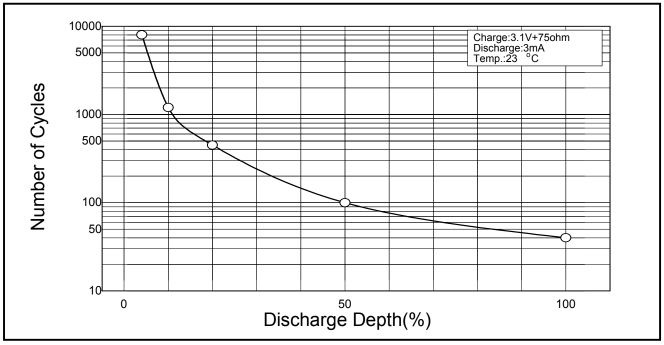
### Charging Voltage vs. Capacity of ML2430



### Temperature Characteristics of ML2430



### Charge/ Discharge Cycle Characteristics of ML2430



### Discharge Characteristics after Continuous Charge of ML2430