Overcoming Low-IQ Challenges in Low-Power Applications

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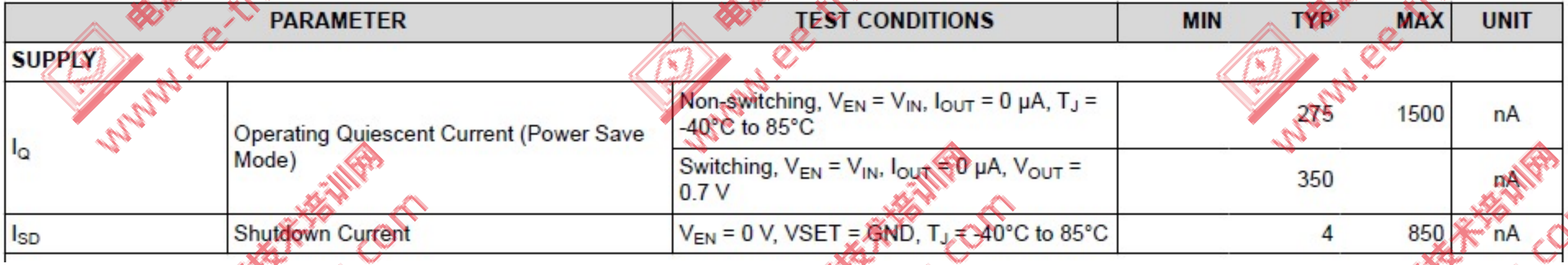
TEXAS INSTRUMENTS

Agenda

- What is IQ?
- Why low IQ creates new challenges?
- How to break low IQ barriers?
- Introduction to new low IQ parts

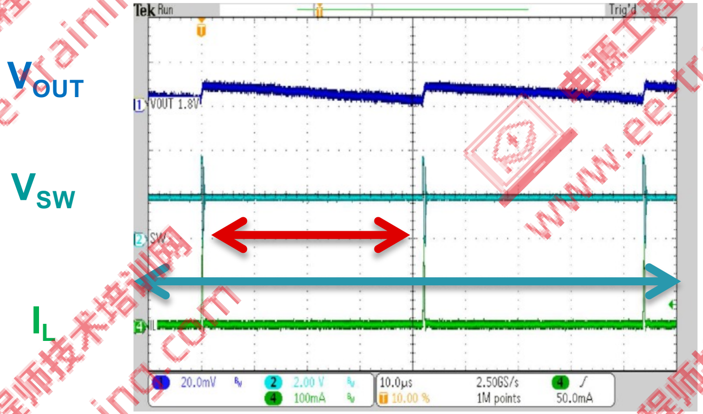
What is IQ?

What is Device IQ?



PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
SUPPLY						
I_Q	Operating Quiescent Current (Power Save Mode)	Non-switching, $V_{EN} = V_{IN}$, $I_{OUT} = 0$ µA, $T_J = -40°C$ to $85°C$		275	1500	nA
		Switching, $V_{EN} = V_{IN}$, $I_{OUT} = 0$ µA, $V_{OUT} = 0.7$ V		350		nA
I_{SD}	Shutdown Current	$V_{EN} = 0$ V, VSET = GND, $T_J = -40°C$ to $85°C$		4	850	nA

https://www.ti.com/lit/gpn/TPS62843

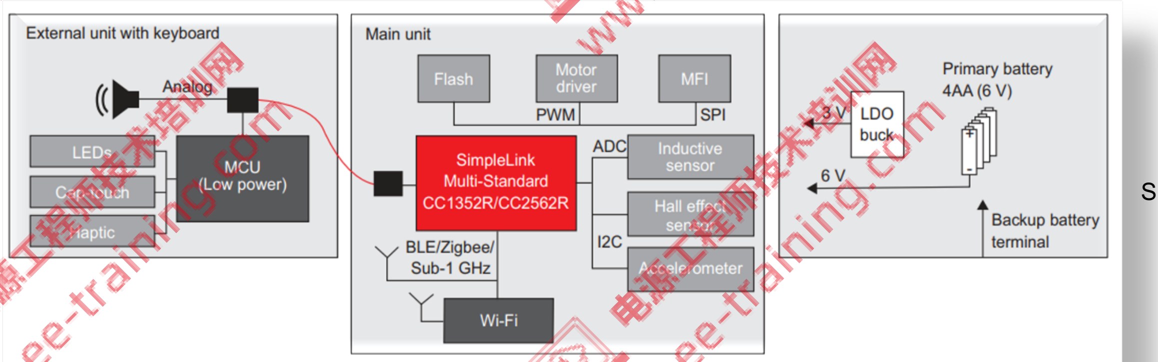


- Device operation at no load
- Quiescent current (non-switching)
- Quiescent current (switching)

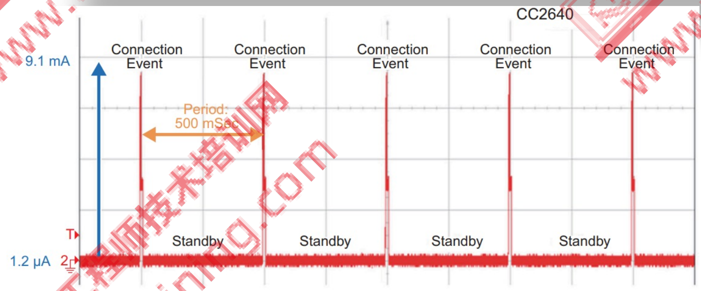
Why it needs low IQ?

https://www.ti.com/lit/wp/slyy203b/slyy203b.pdf

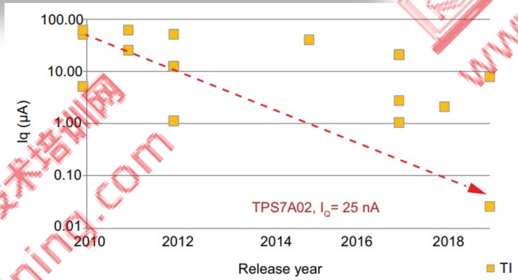
- IQ is the no-load quiescent current, and the most important bottleneck to overcome for duty-cycled low-power systems. Low IQ enables longer battery life.
- Minimizing quiescent current (IQ) is a key factor to reduce power consumption and manage battery life. An Internet of-Things (IoT) sensor node is one of the best examples of why it's important to minimize IQ to extend battery life.



Smart e-lock block diagram



Current consumption vs time in a smart e-lock



5-V LDO IQ over time

Contributors to total IQ

- To determine the total IQ drawn from a battery or power supply, you must consider the always-on functions and leakage sources from capacitors, resistors and inductors.

- Equation 1 can be used to calculate a superset of the input-referred no-load operating currents for almost any regulator as:

$$I_{I(\text{standby})} = I_Q(V_{IN}) + I_{\text{Leakage}}(V_{IN}) + \frac{V_{OUT}}{V_{IN} \times \eta 1} \times \left[I_Q(V_{OUT}) + I_{FB} + I_{LOAD}\right] \quad (1)$$

  - IQ (VIN) is the VIN-referred IQ (the IC data-sheet value).
  - ILeakage(VIN) is the leakage drawn on the VIN pin from capacitors, inductors, diodes or switches.
  - VOUT is the output voltage.
  - VIN is the battery voltage (the input voltage to the LDO, boost or buck-boost converter).
  - η1 is the DC/DC efficiency when the converter is switching.
  - IQ (VOUT) is the IQ drawn on the switching converter's VOUT pin. For an LDO, IQ (VOUT) = 0.
  - IFB is the current of the feedback resistor divider, if applicable.
  - ILoad is the load current potentially present on VOUT in standby mode.

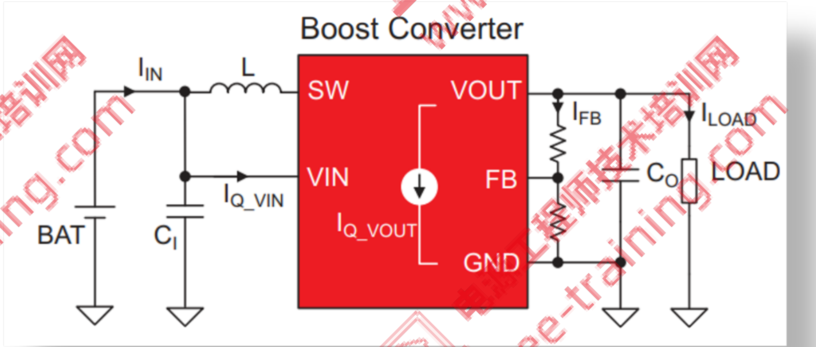


Figure 4. Currents in a boost converter system.

- If you know the battery capacity and have calculated the input-referred standby current, Equation 2 estimates the battery life for a heavily duty-cycled low-power system in standby mode >99.9% of the time as:

$$\text{Battery Lifetime} = \frac{\text{Battery Capacity}}{I_{I(\text{standby})} + I_{\text{Battery leakage}}} \quad (2)$$

Why low IQ creates new challenges?

Transient response

- Power-supply accuracy is often limited by its transient response, which is characterized by its maximum voltage drop, settling time and voltage error integral.
- Low-IQ devices suffer from longer response times because the internal parasitic capacitors need to be charged to new operating points with relatively less current. The worst case is usually a step from no load to the maximum allowed load current.
- Calculating figures of merit (FOMs) helps the designer judge the overall performance of a power regulator.

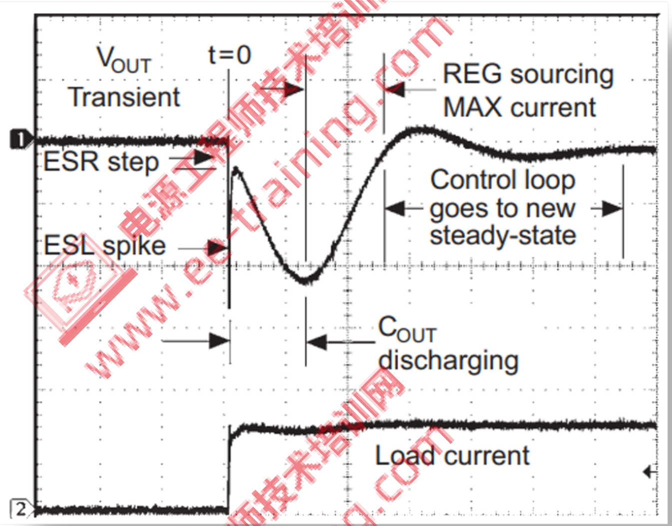


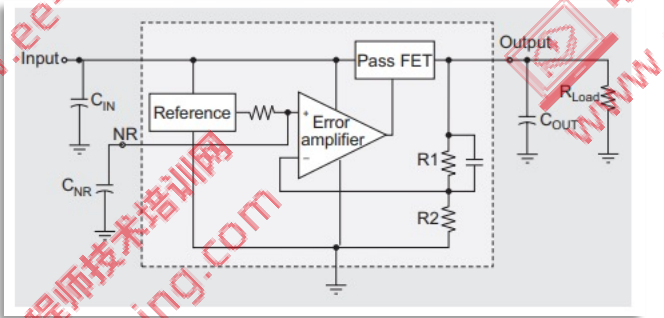
Figure 5. An output voltage transient

$$\text{Transient response dip FOM} = \frac{I_Q \times \Delta V \times C_O}{I_{O\_MAX} \times \Delta I_O} \quad (3)$$

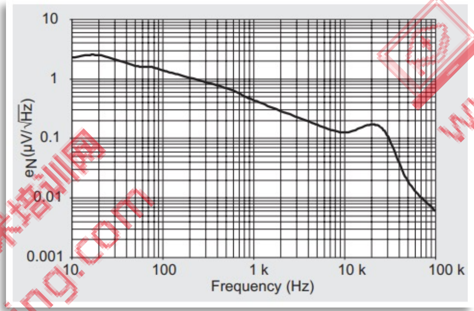
Figure 6. Transient response dip FOM over time for a 5-V buckboost converter

Ripple & Noise

- **Ripple**
- ➢ Another way to enable lower IQ is to enter different power-save modes depending on the load current.
- ➢ Two points of concern are the **voltage ripple** during the transition between power-save modes and the **output-voltage accuracy**.
- **Noise**
- ➢ Another hurdle to overcome is the increased self-noise in amplifiers that accompany lower IQ biasing.
- ➢ Thermal noise
- ➢ Flicker noise
- ➢ A simple method to evaluate the resultant noise for a given IQ –
  - ○ multiply the integrated noise over the frequency range of concern and the IQ at the operating point of interest.



Simplified LDO block diagram

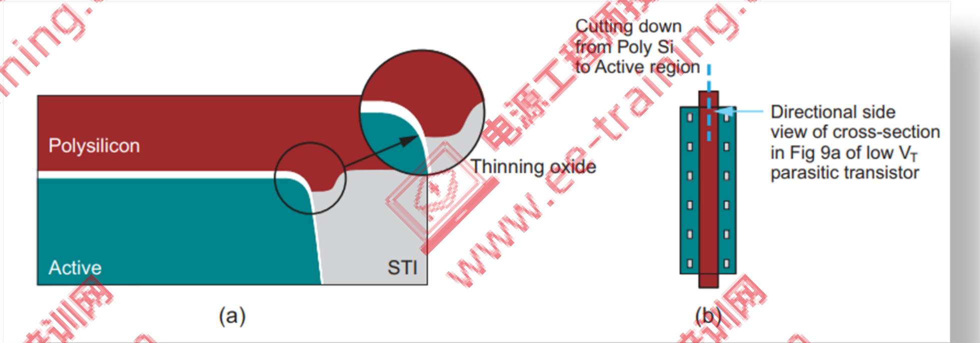


Spectral noise density example.

Other challenges

- **Die size and solution area**
- Decreased IQ may also result in increased board area required for larger passives or IC package sizes.
- An easy method to filter out the best solutions on the market is to apply a simple FOM- IQ * the smallest package area. .

- **Leakage and subthreshold operation**



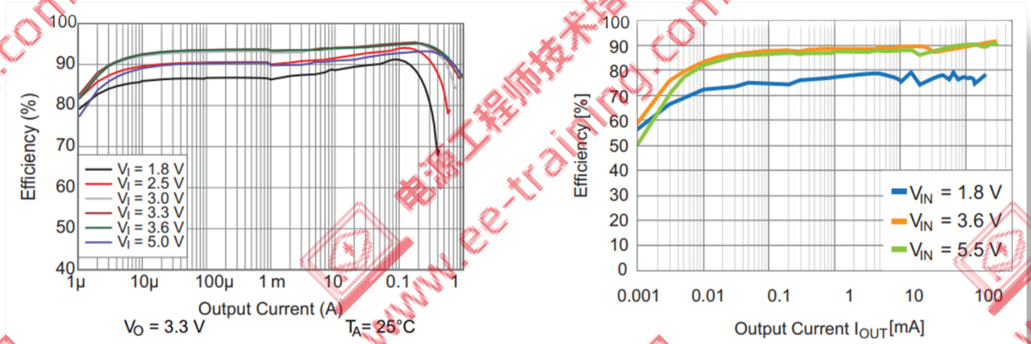
Oxide-thinning-induced parasitic low-VT in 2D cross-section (a); and layout view (b).

How to break low IQ barriers?

How to break low IQ barriers?

Optimizing IQ requires the resolution of multiple, conflicting design challenges. You must meet all of the critical performance specifications in transient response, noise and accuracy, while reducing IQ by orders of magnitude.

- For DC/DC switching converters, look at the power efficiency over load current.
- For LDOs, look at current efficiency over load current.



(a) (b)

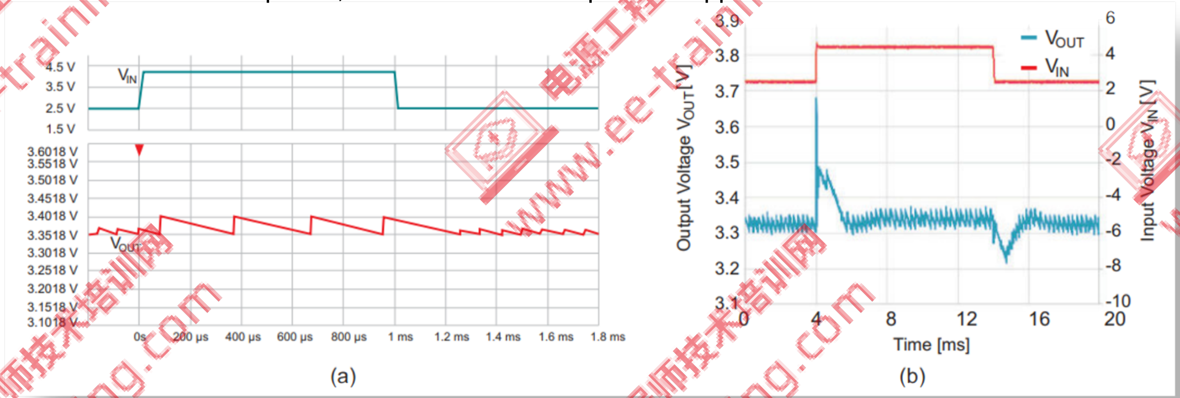
The efficiency for TPS63900 stays above 80% over six decades of load current, starting at 1 µA and hitting a peak efficiency of 96%.

Figure 10. Efficiency of the TPS63900 (a) and competition (b). (Source: TI and competitor data sheets).

Addressing transient response issues

- The key to improving the transient response is to start with the best topology.
  - Using transient detection circuits to adjust bias currents or enable circuitry further reduces both voltage dips at the output and settling times

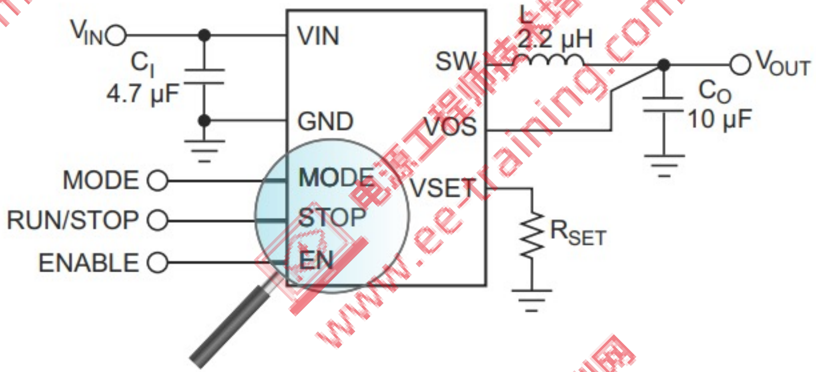
  E.g. TPS61094 monitors dv/dt slopes at the output and adjusts its regulation behavior to optimize the transient performance
  - Reduce the number of current-consuming blocks as much as possible
  - Using sample-and-hold techniques when entering light load and dynamic biasing
  - Another technique uses fast startup circuits. By reducing the startup time of the sample-and-hold reference systems, the on time of the band-gap core and scaling amplifier circuits are reduced significantly.
  - To improve the line transient response, feed-forward techniques are applied



Line transient response with VIN = 2.5 V to 4.2 V, VOUT = 3.3 V, IOUT = 1 mA: TPS63900 (a); competing device (b).

Addressing switching-noise issues

- When designing a high-precision data application, one priority is to control the switching noise of the DC/DC converter, especially in power-save modes with transient bursts that generate a high output voltage ripple.
- The TPS62840 buck converter, which has an IQ of 60 nA, has a STOP pin that immediately stops the regulator switching after the current switching cycle, opening a window of complete switching silence.



Zero switching noise on the TPS62840 from the STOP pin feature.

Addressing other noise issues

- Beyond switching noise, continuous self-noise, with thermal and flicker noise components in the range of 0.1 Hz to 100 kHz, are of concern at lower IQ biasing.
- Because the reference is usually the largest noise contributor, choosing integrated versions of sample-and-hold techniques to create both voltage and current references offer a compelling trade-off between area, noise, IQ and robust performance (no drift) over the life of the device.

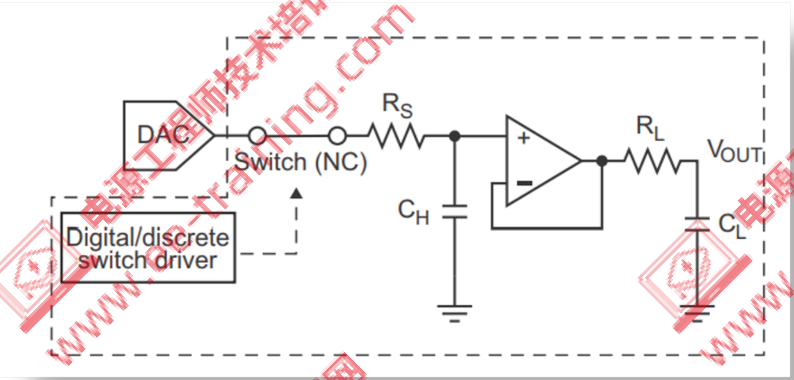


Figure 13. Discrete sample-and-hold DAC system.

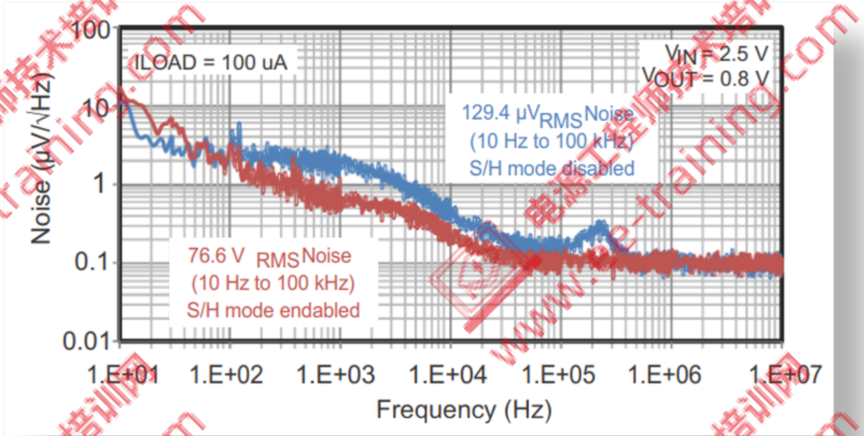
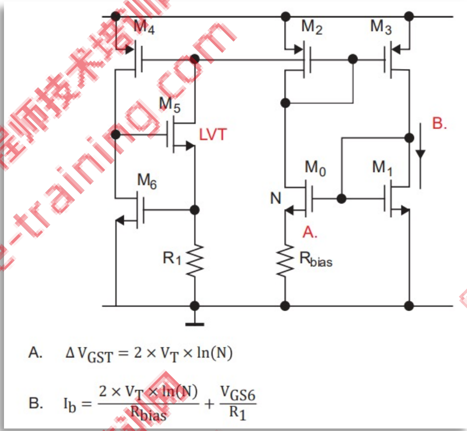


Figure 14. Noise spectrum with and without a sample-and hold reference on the TPS7A02. (Source: TI internal silicon measurements on the TPS7A02)

Addressing die size and solution area issues

- Figure 15 shows a clever implementation of an almost zero-temperature coefficient bias current, creating positive and negative coefficient temperature bias currents with a small voltage bias across resistors R1 and Rbias.
- Figure 16 demonstrates a side-by-side comparison of the typical 0402 capacitor vs the DQN and WCSP package offered for TPS7A02.



A. $\Delta V_{GST} = 2 \times V_T \times \ln(N)$

B. $I_b = \frac{2 \times V_T \times \ln(N)}{R_{bias}} + \frac{V_{GS6}}{R_1}$

Figure 15. Circuit diagram of low-area 1-nA current reference.

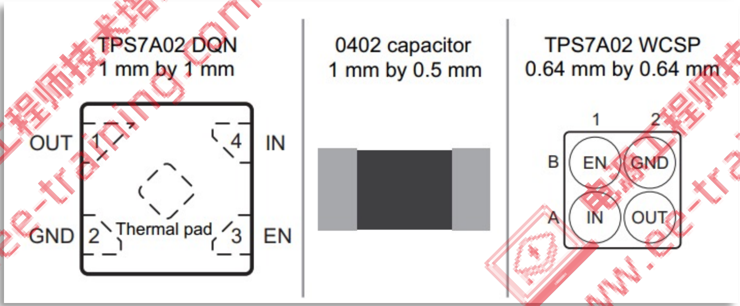


Figure 16. Side-by-side size comparison of TPS7A02 in a DQN package, 0402 capacitor and WCSP package

Addressing leakage and subthreshold operation issues

- High-density resistors and capacitors combined with novel circuit techniques enable a reduction in both IQ and die area.
- Power FETs and digital logic provide low-leakage transistors while simultaneously being optimized for speed;

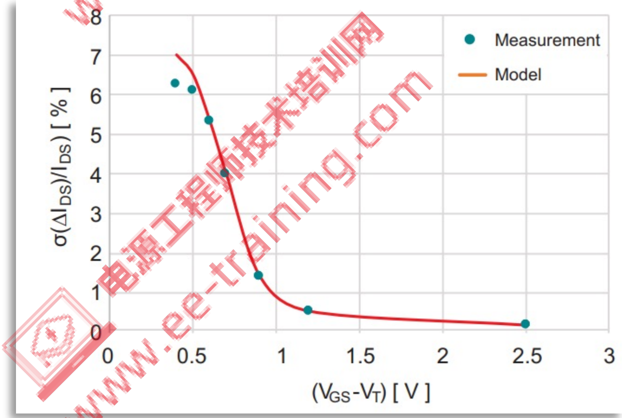
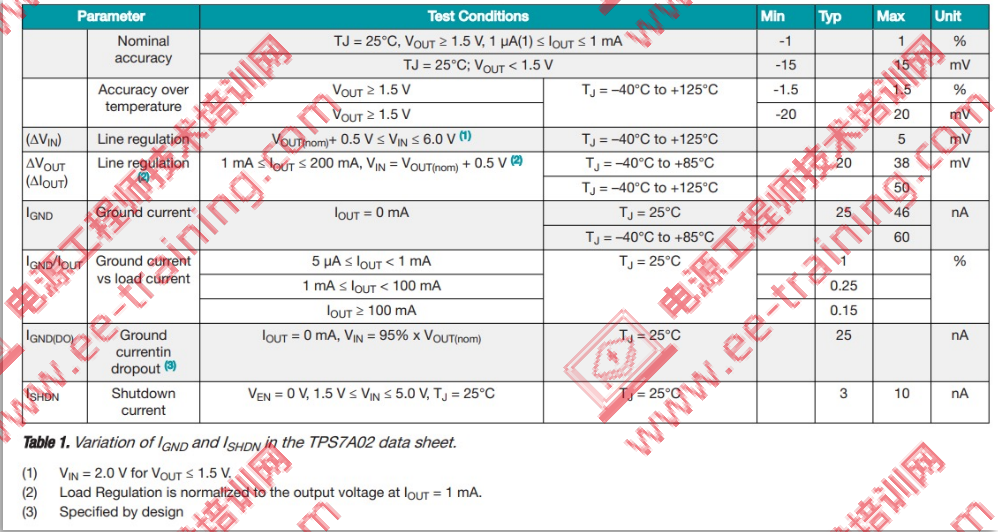


Figure 18. Sigma IDS percentage mismatch vs. VGS – VT .



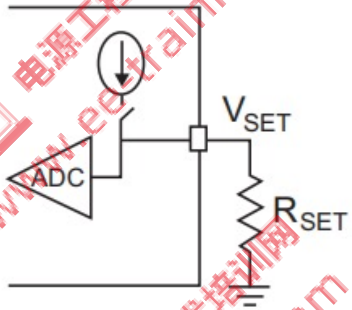
Parameter		Test Conditions		Min	Typ	Max	Unit
	Nominal accuracy	TJ = 25°C, $V_{OUT} \geq 1.5$ V, 1 µA(1) ≤ $I_{OUT} \leq 1$ mA		-1		1	%
		TJ = 25°C; $V_{OUT} < 1.5$ V		-15		15	mV
	Accuracy over temperature	$V_{OUT} \geq 1.5$ V	T_J = –40°C to +125°C	-1.5		1.5	%
		$V_{OUT} \geq 1.5$ V		-20		20	mV
(ΔV_{IN})	Line regulation	$V_{OUT(nom)}$+ 0.5 V ≤ $V_{IN} \leq 6.0$ V (1)	T_J = –40°C to +125°C			5	mV
ΔV_{OUT} (ΔI_{OUT})	Line regulation (2)	1 mA ≤ $I_{OUT} \leq 200$ mA, $V_{IN} = V_{OUT(nom)}$ + 0.5 V (2)	T_J = –40°C to +85°C		20	38	mV
			T_J = –40°C to +125°C			50	
I_{GND}	Ground current	I_{OUT} = 0 mA	T_J = 25°C		25	46	nA
			T_J = –40°C to +85°C			60	
I_{GND}/I_{OUT}	Ground current vs load current	5 µA ≤ $I_{OUT} < 1$ mA	T_J = 25°C		1		%
		1 mA ≤ $I_{OUT} < 100$ mA			0.25		
		$I_{OUT} \geq 100$ mA			0.15		
$I_{GND(DO)}$	Ground currentin dropout (3)	I_{OUT} = 0 mA, V_{IN} = 95% x $V_{OUT(nom)}$	T_J = 25°C		25		nA
I_{SHDN}	Shutdown current	V_{EN} = 0 V, 1.5 V ≤ $V_{IN} \leq 5.0$ V, T_J = 25°C	T_J = 25°C		3	10	nA

Table 1. *Variation of I_{GND} and I_{SHDN} in the TPS7A02 data sheet.*

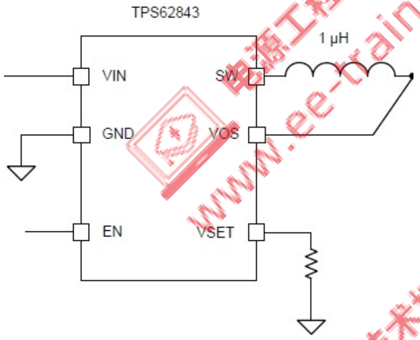
(1) V_{IN} = 2.0 V for $V_{OUT} \leq 1.5$ V.
(2) Load Regulation is normalized to the output voltage at I_{OUT} = 1 mA.
(3) Specified by design

Achieving low IQ, but not losing flexibility

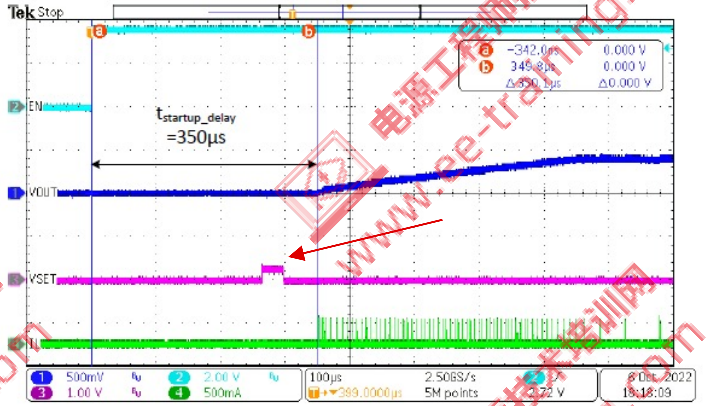
- Flexibility is key in a low-power application design. One such example is changing the output voltage value.
- The traditional way is to use an adjustable external feedback divider, but this will cause not just higher inaccuracy but also higher IQ.
- Modern nanoampere power converters use R2D interfaces, which enable the digitized setting of output voltages without consuming extra current, since the function will shut down after booting the device.



R2D interface



275nA IQ TPS62843 w/ R2D



TPS62843 R2D read during Startup

Conclusion

The key benefits of TI technologies for low IQ include:

- Low, always-on power — long battery run times, enabled by ultra-low leakage process technologies and novel control topologies.
- Fast response times — fast wake-up comparators and zero-IQ feedback control enable fast dynamic responses without compromising low power consumption.
- Reduced form factors — area reduction techniques for resistors and capacitors facilitate integration into space-constrained applications while not affecting quiescent power.

Introduction to new low IQ parts

Applications of Ultra-Low I_Q DC/DC Regulator

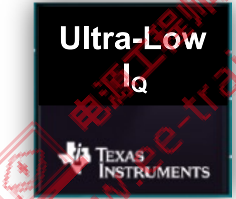
Many battery-powered End Equipments

Grid Infrastructure
- Gas Meter
- Water Meter

Building Automation
- Electronic Smart Lock
- Smart Thermostat
- Wireless Camera

Industrial Transport
- Asset Tracking

Personal Electronics
- Portable Electronics
- Wearables
- Smart Watches



Medical
- Patient Monitor
- CPAP
- Hearing Aid

EPOS
- Smart Shelf / Label

Car Access
- Immobilizer
- Key

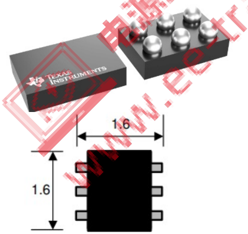
Factory Automation
- Predictive Maintenance
- IoT Sensors

TPS62843x **NEW**

275nA-I_Q , Small size, optimized high efficiency for load(50uA-200mA) Buck Converter

Features

- **1.8V** to 5.5V Input Voltage Range
- **600mA Load Current Capability**
- **275nA Quiescent Current**
- **1.5MHz** switching frequency
  - **1µH: Optimized Efficiency**
  - Down to 4.7-µF Cout
- VSET-Pin to adress 0.4V – 3.6V Output:
  - TPS628436: 0.4 V to 0.8 V
  - TPS628437: 0.8 V to 1.8 V
  - TPS628438: 1.8 V to 3.6 V
- ±1% V_{OUT} accuracy
- Auto transition PFM/PWM
- **6-pin WCSP: 0.8 x 1.05mm, 0.35mm pitch**
- **6-pin SOT563: 1.6 x 1.6mm**

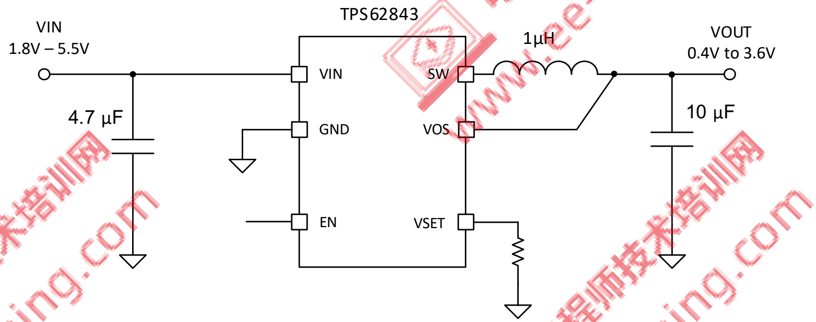


Applications

- Wearable devices/ Hearbales
- Portable Devices
- Battery powered IoT Applications

Benefits

- **Longer Battery runtime by optimized µA-Load Efficiency**
- **Flexible usage by setable output: 0.4V to 3.6V**
- **Smaller & Cheaper Solution: Single-Layer PCB Layout**
- **Small Board space needed (< 5mm² solution size)**
  - **by small chip (0.84mm²)**
  - **and small passives**
- **BOM-Compatible to TPS6280x-Family**



Texas Instruments

TPS62 840 New Ultra-Low I_Q DC/DC converter

1.8V – 6.5V_{IN}, 750mA I_{OUT} , very high light-load efficiency Buck

Features

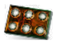
- I_Q: 60nA
- 100% Duty Cycle with 120nA I_Q
- 80% efficiency at 1µA I_{OUT} (3.6V_{IN} to 1.8V_{OUT})

- Selectable Forced-PWM and STOP modes

- 16 x V_{OUT} selectable with VSET
  - ○ TPS62840: 1.8V – 3.3V (100mV steps)
  - ○ TPS62841: 0.8V – 1.55V (50mV steps)
  - ○ TPS62842: 1.8V, 2.2V, 2.4V – 3.6V (100mV steps)
  - ○ TPS62849: 3.4V

- 8 pin SON 1.5x2mm (<17mm² solution size)

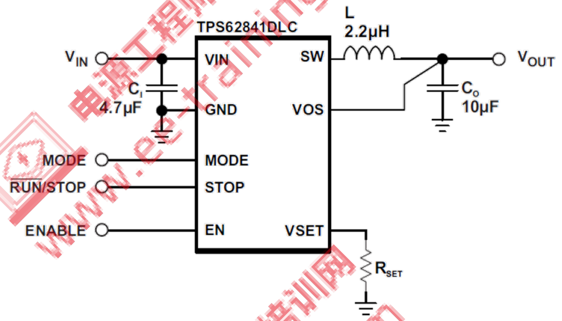
- 6 pin WCSP 1x1.5mm (<14mm² solution size)

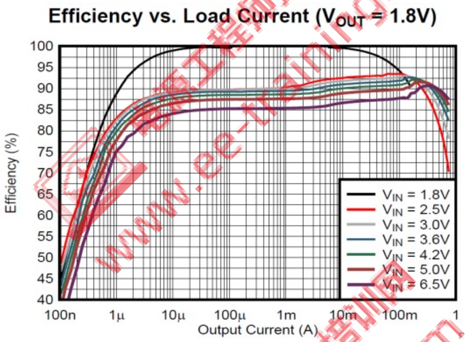


- 8 pin MSOP 3x5mm

Benefits

- Higher light load efficiency → Longer battery life time
- Enables operation of Low Power MCU from various battery configurations: 2s-LiMnO2, 1x LiSOCL2, 4s/2s Alkaline, Li-Po, Coin Cells
- Forced-PWM and STOP function for noise sensitive applications
- Small package / small solution size



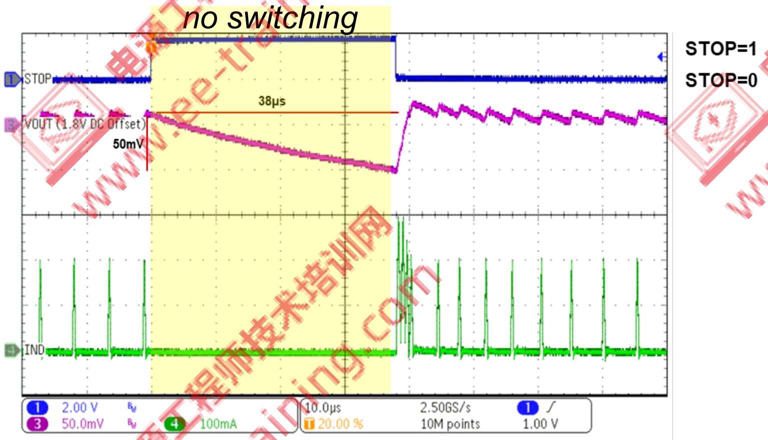


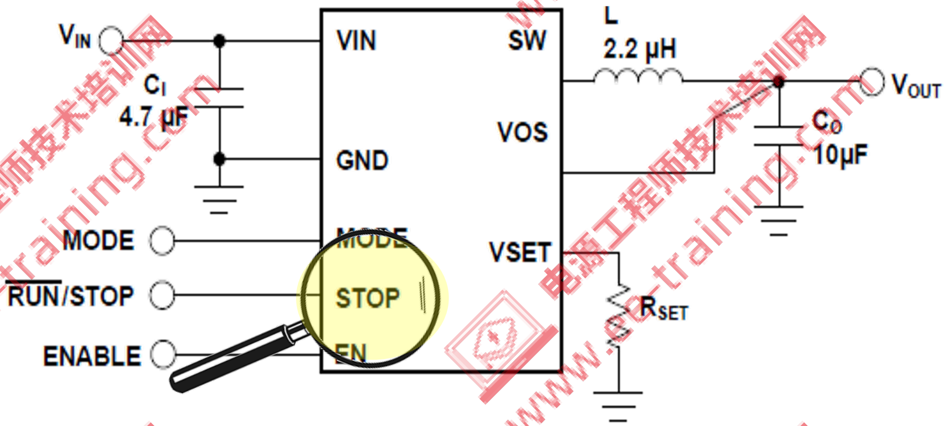
Integrated STOP function

TPS62840

Ripple, noise and distortion produced by power conversion comes from internal power switching.
The STOP function eliminates this switching, reducing the need for filters and its cost.

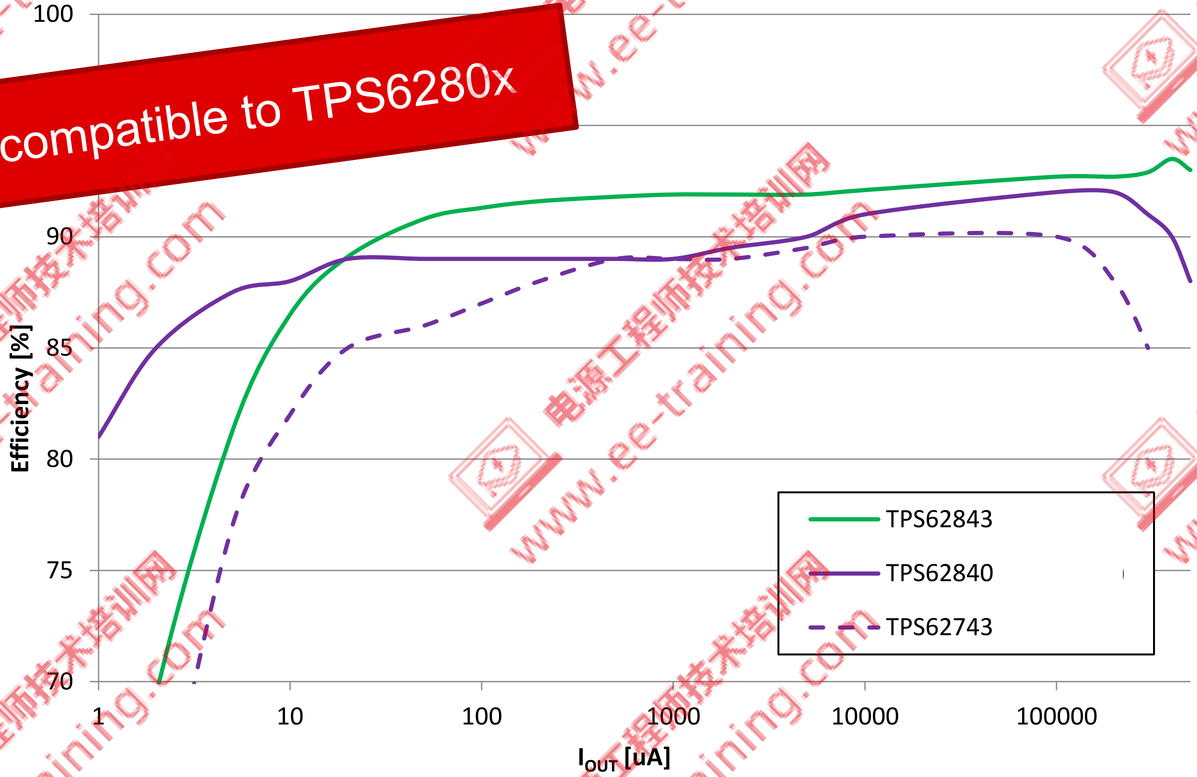
The STOP input pin allows the user to temporarily stop the regulator's switching. The application is powered by the charge available in the output capacitor. No switching noise is generated which could be beneficial in noise-sensitive sampled applications or wireless connectivity.





Next generation ultra-low I_Q buck converter *TPS62843*

Improvement at Ultra-Light Load Condition ($3.6V_{IN}$ to $1.8V_{OUT}$)



pin-compatible to TPS6280x

Texas Instruments

TPS61299X(Q1)

100nA Quiescent Current, 5.5V Boost Converter With Input Current Limit and Fast Transient Performance

FEATURES

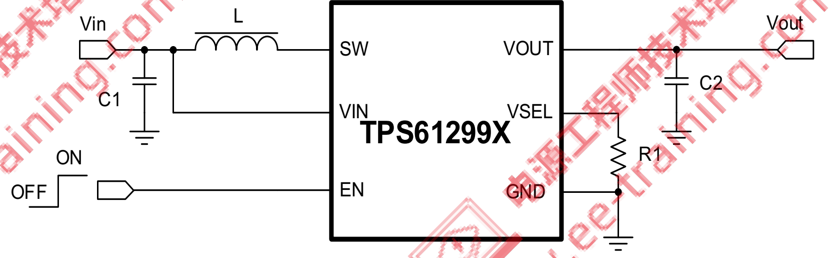
- Input voltage range: 0.7V to 5.5V
- Output voltage range: 1.8V to 5.5V (VSEL pin select output voltage)
  - 2.2V; 3V; 3.3V; 3.5V; 3.6V; 4.5V; 4.8V; 5V; 5.2V; 5.5V
- Input operating voltage down to 150mV with VIN > 0.7V
- 100nA typical quiescent current from VOUT in Boost Mode
- 100nA typical shutdown current from Vin and SW;
- Up to 92% efficiency at VIN = 2 V, VOUT = 3.3 V, and IOUT =10 μA
- Up to 94% efficiency at VIN = 2 V, VOUT = 3.3 V, and IOUT =200 mA
- Different versions for
  - Input current limit: 5mA; 25mA; 50mA; 100mA; 1.2A
- Fast transient perfromance: setting time ~8us at VIN = 3.6 V, VOUT = 5 V Iout = 0A -> 200mA
- True disconnection during shutdown & Short protection
- Automatic PFM/PWM mode transition; Auto pass-through at Vin > Vout
- 6-Pin WCSP (1.2 x 0.8) / SOT563 package (1.2 x 1.6)

APPLICATIONS

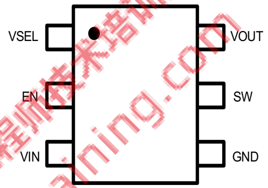
- Super Cap charging
- IoT Devices
- Portable Medical Equipment
- Wireless Sensor
- Zinc-Air/Zinc-Silver/Coin Cell Battery Applications

BENEFITS

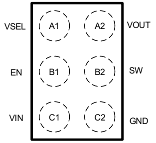
- Input current limit: protect high impedance batteries
- Fast load transient: suitable for AEF application
- 100nA quiescent current: efficiency is about 92% at ~10uA light load



DRL



YFF



Thank you!

Reference links

- https://www.ti.com.cn/cn/lit/wp/zhcy154b/zhcy154b.pdf
- https://www.ti.com/lit/wp/slyy203b/slyy203b.pdf
- https://www.ti.com/lit/an/slyt412/slyt412.pdf
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