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Choosing The Best Operating Mode In An Ultra-Low-I_Q Buck Converter

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Through ultra-low-power techniques and ultra-low quiescent current (I_Q), a stepdown (buck) converter extends the battery run time for many portable devices such as earbuds, sensors and smart meters. But operating with ultra-low power is only half the goal. To be useful, a buck converter must still meet the performance needs of the system, such as responding to load transients from the radio or generating low-enough noise for a data converter.

To do this, the Texas Instruments (TI) TPS62840 ultra-low-power buck converter has numerous operating modes, which are optimized for power consumption and performance under varying operating conditions. Examining this ultra-low-power buck converter with just 60 nA of I_Q, this article describes each of its five operating modes: shutdown, power-save, forced pulse-width modulation (PWM), 100% and stop mode. Furthermore, the article explains their impact on I_Q, their system benefits, and how each mode supplies the required performance while drawing appropriately low currents.

Understanding A Data Sheet's I_Q Specifications

Each operating mode in the TPS62840 consumes a different amount of current, which is specified in the electrical characteristics section of the device's data sheet. Both the header row above the table and the test conditions column in the table detail the applicable operating range for each individual specification. Table 1 shows the electrical characteristics for the TPS62840 buck converter with its operating modes' I_Q. Since the various pins of this IC are cited in this discussion, a functional block and typical application circuit for the TPS62840 are included here for reference (Fig. 1).

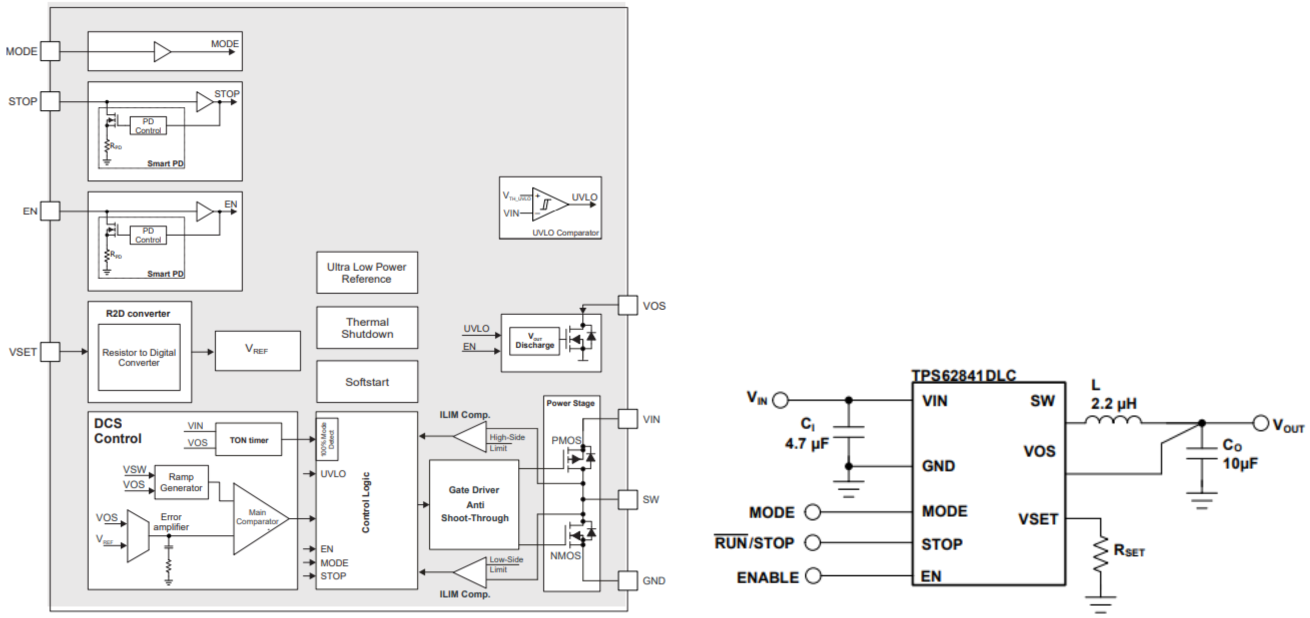

Fig. 1. Internal block diagram and typical application circuit for the TPS62840 ultra-low-power buck converter.

Shutdown Mode

Shutdown mode is the lowest power mode and is entered by pulling the EN pin to a logic-low level. A tiny amount of I_Q is consumed from the input voltage to power only those portions of the device required to detect when the EN pin goes high. For the TPS62840, the device stops switching and discharges the output voltage to ground through its output discharge circuit. Other devices may not have an output discharge function. The TPS62840’s shutdown mode I_Q specification does not include any current discharged at the output voltage.

Looking at row 13 of Table 1, the TPS62840 is specified to consume typically 25 nA of I_Q at 25°C and up to 300 nA of I_Q maximum in shutdown mode. For I_Q, the maximum value almost always occurs at the highest temperature, which is 85°C for this specification.

Table 1. V_{OUT} = 3.6 V, T_J = -40°C to 125°C, STOP = GND, MODE = GND, typical values are at T_J = 25°C (unless otherwise noted).

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
1	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.8 V device switching		60		nA
2	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.2 V device switching		80		nA
3	$I_{Q\_NO\_LOAD}$	No load operating input current (PWM Mode)	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.8 V, MODE = V_{IN} device switching		3		mA
4	I_{Q_VIN}	Operating quiescent current into pin VIN	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = 25°C (DLC package option)		36	100	nA
5	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = 25°C (DLC package option)		56	120	nA
6	I_{Q_VIN}	Operating quiescent current into pin VIN	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = -40°C to 85°C		36	360	nA
7	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = -40°C to 85°C		56	170	nA
8	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, V_{OUT} = 3.3 V device not switching		70		nA
9			EN = V_{IN}, V_{OUT} < 1.5 V device not switching		5		nA
10			EN, STOP = V_{IN}, 3 V < V_{OUT} < 3.3 V T_J = -40°C to 85°C		5	100	nA
11	$I_{Q\_100\%\_MODE}$	Operating quiescent current 100% Mode	V_{IN} = V_{OUT} = 3.3 V, T_J = -40°C to 85°C		120		nA
12	$I_{Q\_VIN\_STOP}$	Operating quiescent current into pin VIN	STOP = High, V_{OUT} = 1.8 V, T_J = -40°C to 85°C		70	175	µA
13	I_{SD}	Shutdown current	EN = GND, shutdown current into V_{IN} VSET = GND, T_J = -40°C to 85°C		25	300	nA

The TPS62840 data sheet includes a graph showing how the typical shutdown mode I_Q varies with input voltage and temperature, shown here as Fig. 2. The data sheet’s graphs show the typical performance, while the table’s minimum and maximum values are worst-case values. These include variations from temperature as well as the normal part-to-part variations that arise due to variations in the manufacturing process.

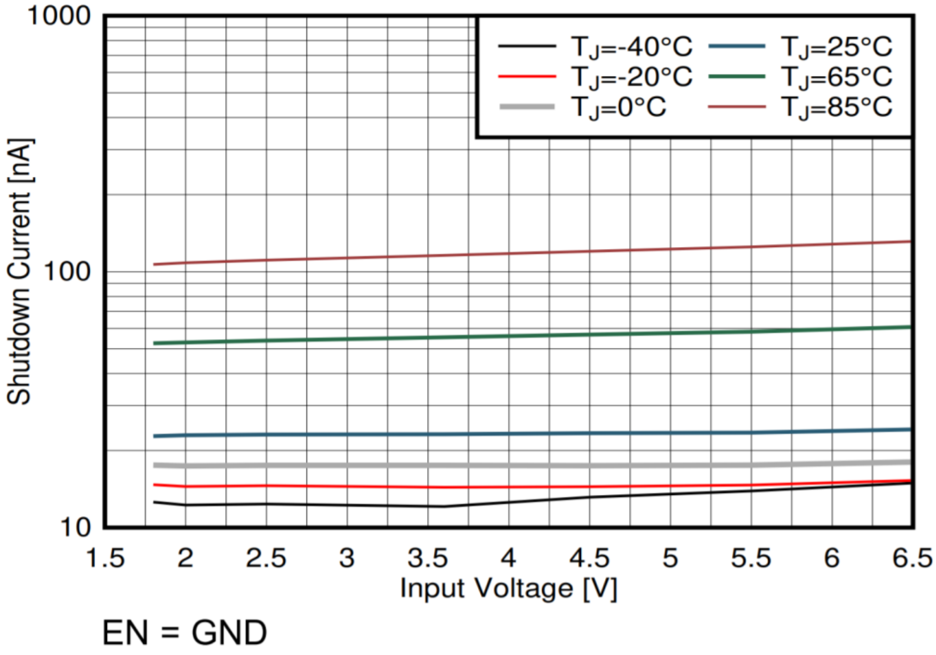

Fig. 2. The TPS62840's shutdown mode I_Q increases with increasing temperatures.

For an ultra-low-power device that consumes very little current when enabled, there are only three reasons for entering shutdown mode:

- First, if the load cannot be disabled or put into a low-power state, the load's supply voltage must be removed to reduce the system's overall power consumption. Disabling the ultra-low-power buck converter or inserting a load switch between the buck converter and the load are two ways to remove the load's supply voltage.
- Second, if there are multiple system rails, shutdown mode provides sequencing between them. Sequencing may be required during system startup, shutdown or both. Sequencing also reduces the inrush current drawn—and the corresponding battery voltage drop—when any power supply starts.
- Third, shutdown mode enables the lowest power system state, which is required for products with a ship mode to enable a lengthy shelf life. When the system is sitting on a shelf in its packaging and waiting to be sold, shutdown mode depletes the battery as slowly as possible.

While these are three reasons to use shutdown mode, leaving the ultra-low-power device enabled keeps the load powered and ready to quickly respond to an input from the user or system, and is desired in many applications.

Power-Save Mode

Power-save mode is the most commonly used operating mode, as it is the lowest-power mode in which the device operates and provides its output voltage. The TPS62840's power-save mode is DCS-Control, which incorporates the advantages of the voltage-mode, current-mode, and hysteretic control topologies while providing a clean entry into its low-ripple power-save mode and superb transient response.[1] Eight Of the 13 rows shown in Table 1 refer to power-save mode. Of these eight, four are for the I_Q at the VIN pin (rows 1, 2, 4, 6) and four are for the I_Q at the VOS pin (rows 5, 7, 8, 9), which connects to the output voltage.

Having specifications for both the input and output voltage I_Q shows that the TPS62840 draws its I_Q from both the input and output. Drawing I_Q from the output is more efficient than drawing it all from the input, since the output voltage is lower than the input voltage. Because the I_Q is a fixed current, drawing it from the lower output voltage results in less power than drawing it from the higher input voltage.

The first two rows of Table 1 show the no-load input current. These specifications are repeated in Table 2. While no-load input current is not technically an I_Q, it is a simple way to show the input current consumed in a real application when the device is switching without any load.[2] The different 60- and 80-nA values result from different output voltages, which are shown in the test conditions.

Table 2. TPS62840's no-load input current.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
1	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.8 V device switching		60		nA
2	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.2 V device switching		80		nA

In rows 8 and 9 of Table 1, the I_Q into the VOS pin changes from 70 nA to 5 nA with a change in the output voltage test condition as repeated here in Table 3. A low output voltage is insufficient to power the device, and all of its I_Q must come from the VIN pin instead. The 60-nA specification draws the I_Q from both VIN and VOS, while the 80-nA specification draws the I_Q entirely from VIN. This shows the power savings that come from drawing part of the I_Q from the output instead of the input.

Table 3. TPS62840's operating quiescent current into pin VOS.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
8	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, V_{OUT} = 3.3 V device not switching		70		nA
9			EN = V_{IN}, V_{OUT} < 1.5 V device not switching		5		nA
10			EN, STOP = V_{IN}, 3 V < V_{OUT} < 3.3 V T_J = -40°C to 85°C		5	100	nA

Note that the 60-nA no-load input current is less than the sum of the I_Q into the VIN and VOS pins: 36 nA plus 56 nA. The VOS pin's I_Q ultimately comes from the input source on the VIN pin. Through its normal switching action, the TPS62840 efficiently converts the input power to an output power and consumes some of this output power as I_Q. Thus, any I_Q on the output must be converted to an equivalent input I_Q. Assuming 100% efficiency, 56 nA of I_Q on the output at 1.8 V becomes 28 nA of I_Q on the input at 3.6 V. Summed with the 36-nA VIN pin I_Q and rounding down yields the 60-nA no-load input current value.

Rows 4 through 7 of Table 1 (repeated here in Table 4) specify the I_Q into the VIN and VOS pins separately, for specific test conditions. The difference between rows 4 and 5 versus rows 6 and 7 is the temperature range and package. As with shutdown mode I_Q, power-save mode I_Q also increases with temperature. Graphs in the data sheet show this increase. While the package does not affect the I_Q value, the package does affect how the device is tested in production. How a parameter is tested affects the minimum and maximum values of that parameter.

Having such an ultra-low I_Q while providing a regulated output voltage is a huge system benefit to ultra-low-power systems and their always-on rails. For example, operating a radio in a low-power state enables the lowest system power consumption. Then, when it needs to transmit or receive, the fast DCS-Control power-save mode quickly responds to the radio's load transients and maintains the output voltage. Through efficient conversion of the input power, and by drawing the I_Q from the output when possible, the TPS62840 enables system operation at incredibly low power levels.

Table 4. TPS62840's operating quiescent current into VIN and VOS pins under different test conditions.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
4	I_{Q_VIN}	Operating quiescent current into pin VIN	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = 25°C (DLC package option)		36	100	nA
5	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = 25°C (DLC package option)		56	120	nA
6	I_{Q_VIN}	Operating quiescent current into pin VIN	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = -40°C to 85°C		36	360	nA
7	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.55 V or V_{OUT} = 1.8 V, device not switching, T_J = -40°C to 85°C		56	170	nA

Forced-PWM Mode

Pulling the MODE pin to a logic-high level enables forced-PWM mode operation. Forced-PWM mode constantly switches the device at its target frequency to regulate the output voltage up or down. Because of the constant switching and accompanying switching losses, efficiency at low output currents is much lower than in power-save mode. This efficiency difference is reflected in the no-load input current specification of 3 mA in row 3 of Table 1 (repeated here in Table 5) and is many orders of magnitude higher than the 60-nA I_Q value in power-save mode.

Table 5. TPS62840's operating quiescent current in forced PWM mode versus in power-save mode.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
1	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.8 V device switching		60		nA
2	$I_{Q\_NO\_LOAD}$	No load operating input current	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.2 V device switching		80		nA
3	$I_{Q\_NO\_LOAD}$	No load operating input current (PWM Mode)	EN = V_{IN}, I_{OUT} = 0 µA, V_{OUT} = 1.8 V, MODE = V_{IN} device switching		3		mA

However, the higher switching frequency results in a lower output-voltage ripple. Both the higher frequency and lower ripple are generally beneficial to data converters and other precision analog systems. If the application requires these performance attributes, the TPS62840 allows the system to dynamically toggle its MODE pin to enter and exit forced-PWM mode as needed.

For example, the system can enable forced-PWM mode when taking a measurement and then enable power-save mode between measurements. Such dynamic control utilizes both the ultra-low-power and low ripple benefits.

100% Mode

The device's 100% mode is entered automatically when the input voltage drops close to the output voltage. This provides the lowest voltage drop from the input to the output, which allows the greatest use of the battery's energy. Row 11 of Table 1 (repeated in Table 6) specifies 120 nA of I_Q in 100% mode. Since the high-side MOSFET is on and connects the input voltage to the output voltage, Table 1 gives a single specification for the total I_Q that flows into both pins, VIN and VOS.

Table 6. TPS62840's operating quiescent current in 100% mode.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
11	$I_{Q\_100\%\_MODE}$	Operating quiescent current 100% Mode	$V_{IN} = V_{OUT} = 3.3$ V, T_J = -40°C to 85°C		120		nA

100% mode is a different operating mode than power-save mode, since the high-side MOSFET remains turned on in 100% mode. Instead of turning off most circuits between switching events, as in power-save mode, 100% mode keeps the gate drivers, current limit and other circuits on. For almost all buck converters, these circuits draw a much higher 100% mode I_Q as Table 7 shows for TI's low-power TPS62125 buck converter. Its I_Q jumps from 13 µA to 230 µA.

Table 7. The TPS62125 I_Q specification in 100% mode is 230 µA, compared to 13 µA in power-save mode.

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
I_Q	Quiescent current	I_{OUT} = 0 mA, device not switching, EN = V_{IN}, regulator sleeps		13	23	µA
		I_{OUT} = 0 mA, device switching, V_{IN} = 7.2 V, V_{OUT} = 1.2 V, L = 22 µH		14		µA
I_{ACTIVE}	Active mode current consumption	V_{IN} = 5 V = V_{OUT}, T_A = 25°C, high-side MOSFET switch fully turned on (100% mode)		230	275	µA

The TPS62840 has been specifically designed to not have such an increase in I_Q in 100% mode. The 120-nA typical specification provides much longer battery run times for numerous applications, such as creating:

- 3.3-V V_{OUT} from a single-cell, 3-V to 4.2-V lithium-ion battery, which is in 100% mode at the end of its discharge.
- 3.3-V V_{OUT} from a single-cell 3.6-V lithium primary battery, such as lithium thionyl chloride ($Li\text{-}SOCl_2$) or lithium manganese dioxide, ($Li\text{-}MnO_2$) whose voltage varies below 3.3 V with decreasing temperatures.
- 1.8-V V_{OUT} from two AA or AAA series alkaline cells, which are in 100% mode at their end of discharge.

Such runtime increases are best shown in the efficiency graphs in the TPS62840 data sheet, which include 100% mode. Fig. 3 shows that nearly 100% efficiency is possible when the input voltage decreases to the 3.3-V output voltage.

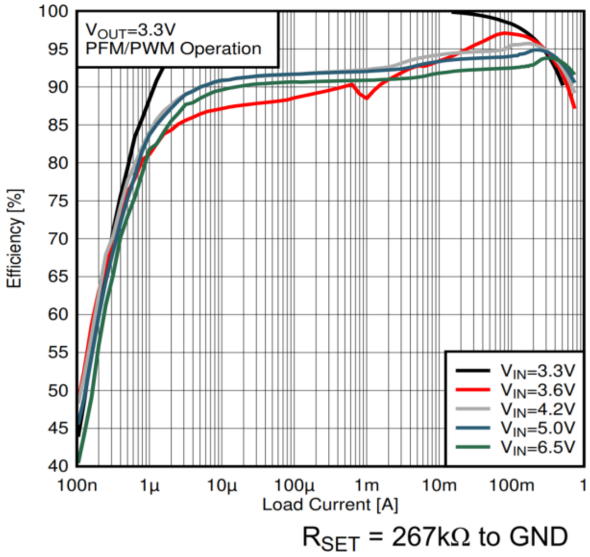

Fig. 3. The TPS62840's 120 nA of I_Q in 100% mode enables nearly 100% efficiency.

Stop Mode

The TPS62840's stop mode is a novel operating mode that is activated by pulling the STOP pin to a logic-high level. This immediately stops the device's switching but does not activate the output discharge nor turn off the device. When the STOP pin goes low again, the TPS62840 immediately resumes switching without any delay or soft start.

Stop mode is designed to be intelligently controlled by the system. The system enters stop mode to eliminate all switching noise in order to take a noise-free measurement, which can therefore be more accurate. Once the measurement is complete, the system exits stop mode and the TPS62840 quickly brings the output voltage back to its setpoint. In stop mode, there is nothing supplying the output with power—the output voltage decays from the load drawing power out of the output capacitors. Fig. 4 shows stop mode's entry and exit.

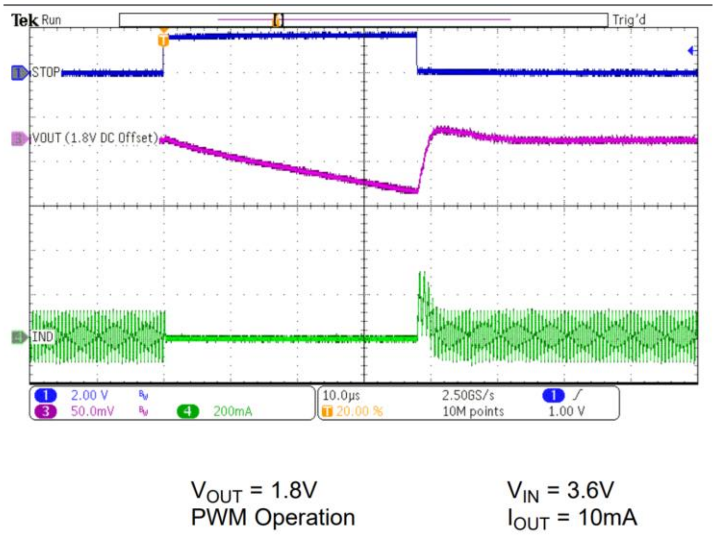

Fig. 4. The TPS62840 enters and exits stop mode almost instantaneously in order to provide a noise-free window.

The TPS62840's stop mode is designed to minimize the I_Q drawn from the output, as well as to provide a very fast return to normal operation. The 5-nA VOS pin I_Q from row 10 of Table 1 (repeated in Table 8 below) enables more power for the load to operate from, while the fast exit from stop mode keeps the voltage high enough for the load to operate. To have a fast exit from stop mode, the TPS62840 does not turn off many internal circuits. This makes the VIN pin's I_Q much higher at 70 µA (see row 12, again in Table 8). Since stop mode is used dynamically, this high I_Q does not significantly affect the overall battery run time.

Table 8. Comparing the operating quiescent current into pin VOS versus that into pin VIN during stop mode.

Row	PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
	SUPPLY						
8	I_{Q_VOS}	Operating quiescent current into pin VOS	EN = V_{IN}, V_{OUT} = 3.3 V device not switching		70		nA
9			EN = V_{IN}, V_{OUT} < 1.5 V device not switching		5		nA
10			EN, STOP = V_{IN}, 3 V < V_{OUT} < 3.3 V T_J = -40°C to 85°C		5	100	nA
11	$I_{Q\_100\%\_MODE}$	Operating quiescent current 100% Mode	V_{IN} = V_{OUT} = 3.3 V, T_J = -40°C to 85°C		120		nA
12	$I_{Q\_VIN\_STOP}$	Operating quiescent current into pin VIN	STOP = High, V_{OUT} = 1.8 V, T_J = -40°C to 85°C		70	175	µA

Conclusion

Operating the power supply with ultra-low I_Q lengthens the time between battery replacements (for primary batteries) or battery recharges (for rechargeable batteries). Through attentive design of the ultra-low-power buck converter and its five operating modes (shutdown, power save, forced PWM, 100% and stop), the system meets both its power consumption and performance requirements.

References

1. "High-efficiency, low-ripple DCS-Control offers seamless PWM/power-save transitions" by Chris Glaser, Analog Design Journal SLYT531, 3Q 2013.

2. "I_Q: What it is, what it isn't, and how to use it" by Chris Glaser, Analog Design Journal SLYT412, 2Q 2011.

About The Author

Chris Glaser is a senior applications engineer for TI's Low Power DC-DC group and a member of the group technical staff. In this role, he supports customers, designs evaluation modules (EVMs), writes application notes, trains field engineers and customers, and generates technical collateral to make TI parts easier to use. He received his bachelor's degree in electrical engineering from Texas A&M University in College Station, Texas.

For more information on minimizing current consumption in buck converter, see How2Power's Design Guide, and do a keyword search on quiescent current.