Addressing Performance Challenges in Nano-I_Q Systems

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This paper highlights various design mechanisms to achieve nano-I_Q (quiescent current) in different power applications along with its challenges.

At a glance

1 **The importance of nano-I_Q in different power applications**

The need to improve battery life with every device generation is increasing, driving requirements to lower I_Q.

2 **Achieving nano I_Q in industrial BMS monitors**

By switching to power modes where essential functions of the device is enabled only when needed, and utilizing circuit level innovations to reduce I_Q.

3 **Achieving nano I_Q in voltage supervisors**

Nano-I_Q is required to enable longer battery life, for always-on monitoring, while at the same time low latency is required for rapid fault reporting.

When a chip is in standby mode, its power consumption is defined by its low quiescent current (I_Q), which refers to a circuit's quiet state when it isn't driving any load. Low I_Q extends the length of standby operations in battery-powered automotive and industrial components such as battery management system (BMS) monitors, BMS chargers, voltage supervisors and DC/DC converters. But these devices do need to consume a certain amount of I_Q in standby mode in order to sustain high-priority functions and essential functional safety features, along with fast system wakeup to active mode.

The importance of nano-I_Q in different power applications

The need to improve battery life with every device generation is increasing, driving requirements for lower I_Q. These devices can be configured to work in normal mode, sleep/standby mode or shutdown mode. Normal mode only accounts for a very small portion of a power application's mission profile [1]; these types of products are in standby mode most of the time. The current draw from the power supply can be several milliamperes in normal mode where there will be bursts of high-speed communication, and several nanoamperes when going into sleep or standby mode. Nanoampere-level working modes can conserve power to support longer battery life.

This paper discusses design mechanisms to achieve nano-I_Q in different power applications such as industrial and automotive BMS battery voltage monitors, chargers, DC/DC converters and voltage supervisors, along with challenges. On one hand, nano-I_Q is required to enable longer battery life; on the other hand, the integrated circuit (IC) needs to consume a certain amount of I_Q to sustain functionalities such as system wakeup.

Achieving nano I_Q in industrial BMS monitors

Many battery-powered products such as power tools and e-bikes are characterized by the need to balance functionality and I_Q in different power states. For example, a power tool in an active state (with the trigger pull on) may consume amperes of current, rendering the I_Q of the battery monitor used in the power tool negligible with respect to the rest of the system. However, this same battery-powered power tool may be sitting on a table for hours or days in sleep mode, with basic protection features enabled. The power tool should also have the ability to respond quickly to a trigger pull. In such a low-power state, the I_Q consumed by the BMS monitor becomes far more important.

By having a sleep mode that still has active protections; an enabled voltage regulator (to retain memory in the system microcontroller [MCU]); and duty-cycled voltage, current and temperature measurements through analog-to-digital converters, the system is still fully protected and ready to respond rapidly, while being able to cut power consumption by a factor of 10 or more relative to active mode. TI industrial monitors have a variety of sleep mode options, allowing you to choose whether to keep protections active (which lets you keep the discharge path enabled); the low-dropout regulator enabled (to allow the system MCU to retain memory and recover within microseconds instead of milliseconds); and duty-cycle options for voltage, current and temperature measurements for a safe, operational sleep mode that can be tailored to optimize power and performance.

Achieving nano I_Q in automotive BMS monitors

The battery control unit (BCU) generally has the BMS's primary MCU on it and is powered by a 12V battery. The MCU cannot run off of 12V, so there will be a DC/DC converter or power-management integrated circuit on the board to generate its power supply. The BMS bridge device that translates Serial Peripheral Interface/Universal Asynchronous Receiver Transmitter communication protocols from the MCU to the isolated daisy chain for the cell monitors is also on the BCU.

The 12V battery charges while a vehicle is motion, so the current consumption from the 12V rail is less important. When the car is parked and not charging, the high-voltage contactors are open, so the >400V battery is disconnected from the system and cannot charge the 12V battery. Despite this, the 12V battery must still supply the BCU and other always-on features (such as key fob locking or unlocking) for unknown periods of time. Low power consumption is important for these types of always-on devices.

Typically, original equipment manufacturers (OEMs) do not want to draw more than 100μA average current from the 12V battery for all of the always-on features. Turning off the BCU completely would minimize BMS power consumption, but would leave the system unable to react if a cell became damaged and dangerous. Instead, OEMs put the MCU into an extremely low power state and rely on the bridge device's reverse wakeup capability. This feature, as shown in **Figure 1**, allows the cell monitors to alert the bridge device if a critical fault occurs, and the bridge device in turn wakes the MCU so that it can respond to the fault.

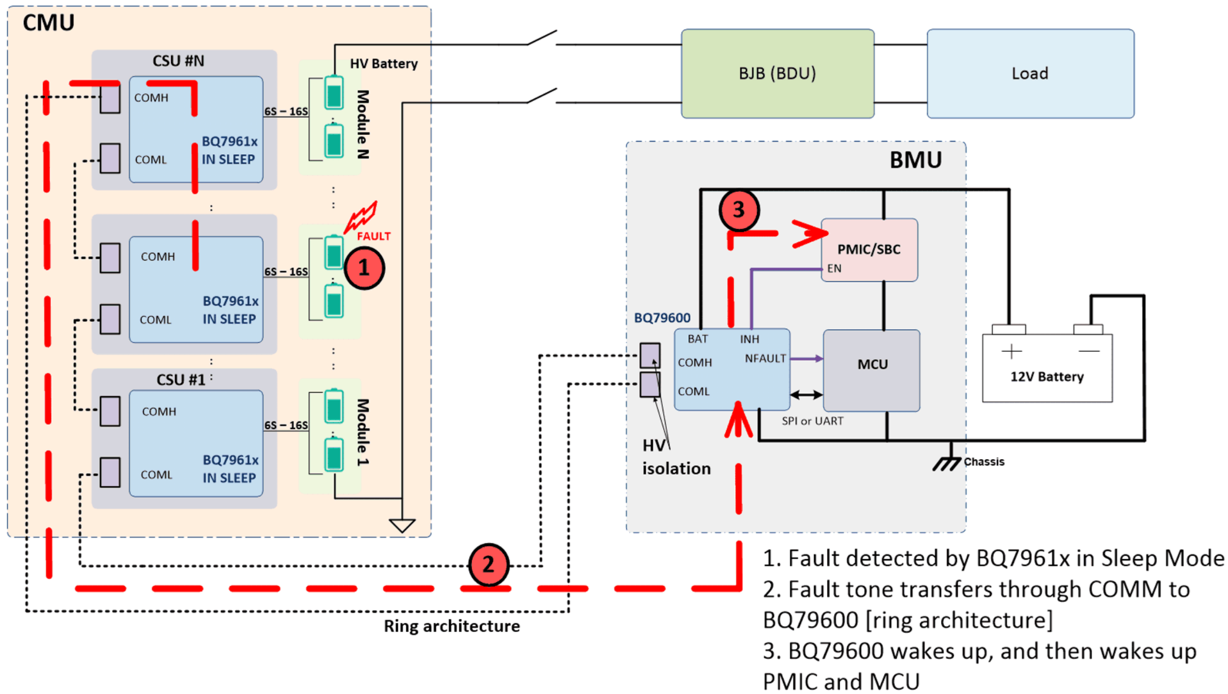

Figure 1. *Reverse wakeup.*

The lower the power consumption of the bridge device, the longer the car can stay parked and its batteries safely monitored without completely draining the 12V battery. The current consumption of the TI BQ79600 is <7µA in sleep mode, which reduces the risk of the 12V battery fully discharging.

Achieving nano I_Q in industrial home automation chargers

Our homes are getting smarter by using internet-connected devices to enable the remote monitoring and management of appliances and systems. The video doorbell, an essential smart home accessory, provides high-definition images and two-way audio communication so that homeowners can greet visitors from their smartphone. While most video doorbells are hardwired to a 12V to 16V supply, many consumers are seeking solar- or battery-powered video doorbells when the existing wiring or transformer is out of date or incompatible. The battery is normally very small to support wireless connectivity and the doorbell button press. TI's BQ25622 and BQ25638 buck chargers have an I_Q of 1.5µA in battery-only mode and 100nA in shutdown mode, with power path to maximize and extend battery run time throughout the product's life cycle.

Enabling the essential functions of the device only when needed reduces I_Q in these chargers, which have a function to monitor the battery temperature through the TS pin for safety reasons. As shown in Figure 2, a switch internal to the chip isolates the external thermistor network connected to the TS_BIAS pin from the 5V REGN pin. This architecture helps eliminate 99% of the thermistor bias current affecting charger I_Q by enabling the internal switch with a 1% duty cycle.

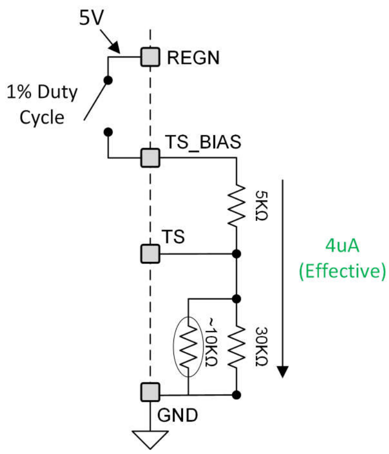

***Figure 2.** TS_BIAS pin in the BQ25622 and BQ25638.*

Turning off the system voltages while maintaining battery power in ship mode can reduce I_Q even further. As shown in **Figure 3**, the BQ25622 and BQ25638 have an integrated, bidirectionally blocking internal field-effect transistor (FET) (Q4) that isolates the battery from the system in its off state. Ship mode is useful not only when the product is about to be boxed at the factory, but also when the device is low on battery, or when the user wants to power off the product.

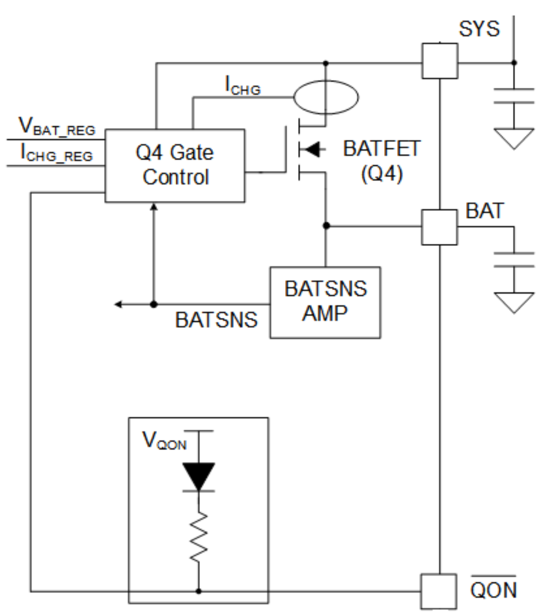

***Figure 3.** BQ25620 block diagram.*

Achieving nano I_Q in automotive BMS chargers

In 2018, the European Union mandated that all cars released in the European market be equipped with an emergency call (eCall) system, which will automatically contact emergency responders in the event of a serious road accident, send GPS coordinates to local emergency services, and wirelessly send airbag-deployment and impact-sensor information. The eCall system has its own battery, independent of the vehicle battery, which must have enough energy to make a 10- to 15-minute phone call, remain on the cellular network for 60 minutes after the initial call, and operate at any time. The **BQ25171-Q1** charger IC plays an important role by charging the eCall battery when the vehicle is on. When the vehicle is off, this charger IC will go into sleep mode and consume only 350nA from the battery. Low I_Q helps extend eCall standby times for emergency readiness.

Achieving nano I_Q in voltage supervisors

In standby mode, automotive OEMs have a 100µA budget for all of the electronics sitting on the supply voltage rail, which could include supply supervisors, load switches, protection transient voltage suppression diodes and DC/DC converters. Nano-I_Q levels in voltage supervisors can help automotive OEMs meet this system-level standby-mode I_Q budget. While the standby I_Q is lowered, the voltage supervisor device cannot relax its standby fault response time. Functional safety requirements specify the device's fault response, characterized by the fault-tolerant time interval from detection to reporting a failure, to scale from the 100µs range to the sub-10µs range.

Conventional supply voltage supervisor solutions with a 1.5% threshold detection accuracy have used a configurable potential divider with discrete resistors on the printed circuit board (PCB). To reduce system I_Q, the values of these discrete resistors need to be scaled up to several tens of megaohms. Since PCB designers do not typically add high-impedance sense-resistor ladders to their boards given area constraints, the resistor ladders are integrated onto the die of the TPS37-Q1 window supervisor. Low I_Q becomes possible on the reference path by duty-cycling the voltage reference and storing the reference on a capacitor, and by constructing the internal sense-resistor ladder as a nonlinear resistor ladder reconfigured between a constant-resistance region into a constant-current region to create a very high-impedance sense ladder at higher voltages.

Wide-V_{IN} window supervisors such as the TPS37-Q1 need to handle voltage swings between external high-voltage input and internal subregulated voltages. Dynamic circuits detect both rise and fall transitions to boost the performance of the level shifters between the external high voltage and internal regulated domains into a temporary turbo mode to improve system response times while still supporting low I_Q.

Achieving nano I_Q in industrial and personal electronics DC/DC converters

In battery-powered systems such as metering systems, smoke detectors, smartwatches, medical sensors and hearing aids, one or two voltage rails are always enabled to power the system MCU, an important sensor, or perhaps a communication bus. These always-on rails need to have very high efficiency to extend the battery run time, making the reduction of I_Q very important.

The TPS62843 buck converter is optimized for load currents from 50μA to 300mA, has a power-save mode, an operating I_Q of 275nA and 4nA of shutdown current. The TPS63901 buck-boost converter and TPS61299 boost converter have an input current-limiting feature to protect batteries that do not support high peak currents such as coin-cell batteries. The TPS63901 converter has a dynamic voltage scaling feature that enables switching between two output voltages during operation, saving power by using a lower system supply voltage in standby mode. As shown in Figure 4, a resistor-to-digital (R2D) circuit in these DC/DC converters sets the output voltage, which helps eliminate leakage current in the feedback resistors, achieves a smaller solution size, and lowers design costs (because you need one less resistor to select the output voltage).

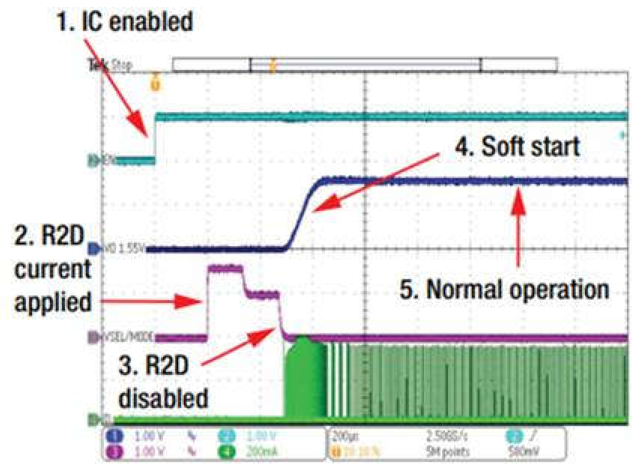

Figure 4. The power-supply IC is enabled, followed by R2D circuit operation with two current source levels, soft start and normal operation.

Figure 5 shows the graph of the ultra-low operating I_Q of the LMR36502 buck converter and the TPSM365R15 buck module. The operating I_Q of 4μA remains relatively constant over the entire operating voltage range of 20V to 60V where the always-on rails need to operate helping extend the battery life.

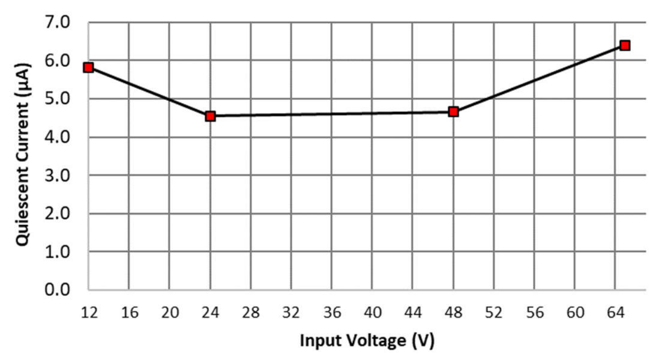

Figure 5. The LMR365R0X and TPSM365R15 IQ at FSW = 1MHz and VOUT = 3.3V

Achieving nano I_Q in automotive DC/DC converters

There are many always-on automotive applications such as sensors, e-call systems and zone control units where long standby time and high efficiency at light loads are very crucial. The LMQ66430-Q1 buck converter is designed to overcome these challenges, achieving >85% efficiency at 1mA loads and allowing an unloaded typical current consumption of 1.5μA at 13.5V_{IN}. The IC runs an impedance check at startup on the VOUT/FB pin. If no external feedback resistors are detected, the device will automatically use an internal feedback network that sets a fixed 3.3V or 5V output voltage, which helps minimize leakages through the feedback network and reduces I_Q. The LMQ66430-Q1 uses an internal low-dropout regulator (LDO) to provide power to the internal circuitry for the IC. Rather than powering the LDO with input voltage and taking the efficiency hit, the LMQ66430-Q1 leverages the same voltage from the VOUT/FB pin to power the internal LDO, which then biases all internal circuitry in order to minimize the total I_Q.

Another buck converter, the **TPS62903-Q1**, uses an R2D interface to set the output voltage, enabling a reduction in leakage current. The TP62903-Q1 seamlessly transitions to power-save mode as the load decreases. In this state, the IC operates in pulse-frequency modulation (PFM) mode by reducing the switching frequency to maintain high efficiency, as shown in **Figure 6** under light-load conditions. This reduces the typical I_Q to 4μA.

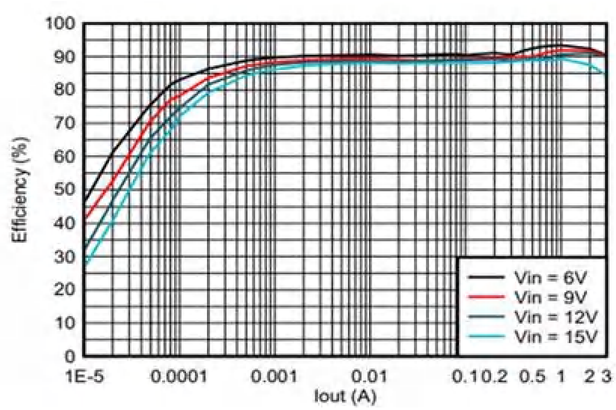

Figure 6. *Efficiency versus output current (3.3VOUT at 2.5MHz, 1μH, automatic PFM or pulse-width modulation).*

Conclusion

The combination of nano-I_Q and the performance of the high-voltage power chips enabled by TI's process technologies helps extend the length of standby operations in several types of power applications. It is very important to understand the mission profile of the final product to set the I_Q target for the system or IC design.

References

1. Texas Instruments: ***Overcoming Low-IQ Challenges in Low-Power Applications***.
2. Zhou, D. et al. "Mission Profile Based System-Level Reliability Analysis of DC/DC Converters for a Backup Power Application." IEEE Transactions on Power Electronics 33, No. 9 (September 2018).

Additional resources

- For more information about low quiescent current, visit **Low quiescent current (I_Q)**.
- Read the technical article, **3 ways low-IQ technologies extend battery life without compromising system performance**.

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