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Introduction

The *Analog Applications Journal* is a digest of technical analog articles published quarterly by Texas Instruments. Written with design engineers, engineering managers, system designers and technicians in mind, these "how-to" articles offer a basic understanding of how TI analog products can be used to solve various design issues and requirements. Readers will find tutorial information as well as practical engineering designs and detailed mathematical solutions as they apply to the following product categories:

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Analog Applications Journal articles include many helpful hints and rules of thumb to guide readers who are new to engineering, or engineers who are just new to analog, as well as the advanced analog engineer. Where applicable, readers will also find software routines and program structures.

Closed-loop motor control: An introduction to rotary resolvers and encoders

By Dwight Byrd
Precision Data Converters

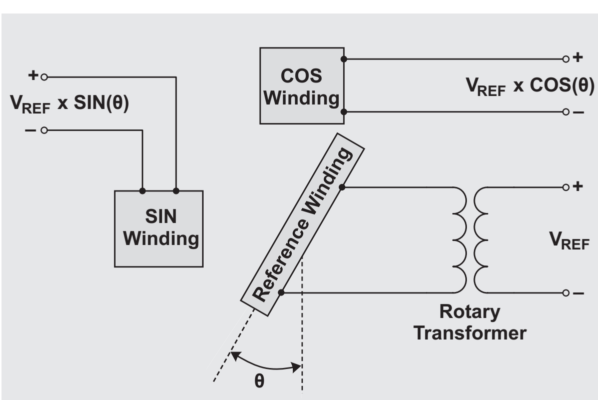
Introduction

Is your motor spinning at the intended rate? Closed-loop motor control systems continue to answer this question, as there tends to be a closed-loop system implemented wherever a motor spins. Whether the end system is an automobile (assisted parallel parking with computer controlled steering), a satellite (positions satellite to lock on to a specific signal), or factory floor machinery (a pick-and-place machine), the position feedback sensor is an intrinsic element in the total motor-control system. There are many types of motor control, but this article discusses two that implement an analog signal chain around the position sensor: the resolver and the encoder.

Resolver

Before discussing the signal-chain solution for a resolver, consider its basic operation in Figure 1. The resolver (in this case, a transmitter unit), is made up of three distinct coil windings: the reference, the sine (SIN), and the cosine (COS). The reference winding is the primary winding that, through a transformer known as the rotary transformer, is excited by an AC voltage applied to the primary side of the transformer. Since the rotary transformer then passes the voltage off to the secondary side of the transformer, no brushes or rings are needed. This increases the overall reliability and robustness of the resolver.

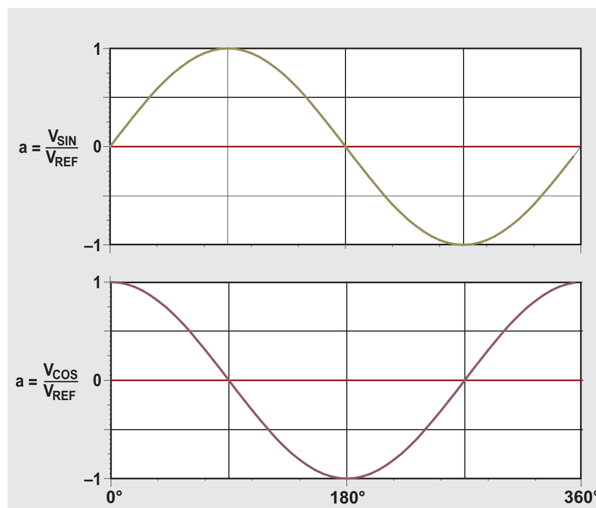
Figure 1. Simplified mechanical schematic of a resolver transmitter unit



The reference winding is mounted on the motor shaft. As the motor spins, the voltage output from the SIN and COS windings change according to the shaft position. The SIN and COS windings are mounted 90° from each other in relation to the shaft. As the reference winding spins, the angle of difference between the reference and SIN/COS windings change, represented as the theta rotation angle or θ in Figure 1. The voltages induced upon the SIN and COS windings are equivalent to the reference voltage multiplied by the SIN winding and COS winding of angle theta.

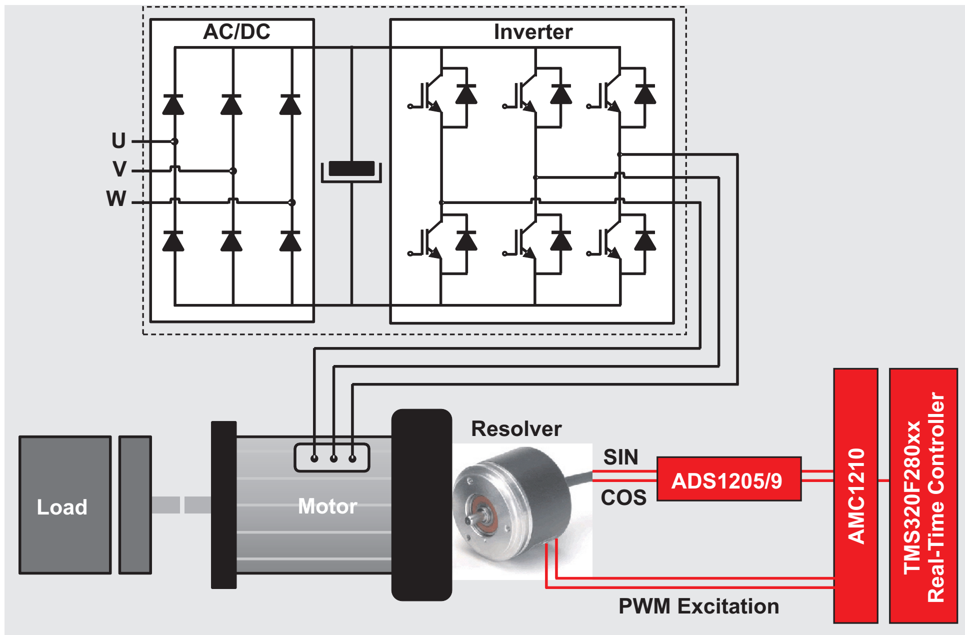
The induced output voltage waveforms are shown in Figure 2. They show the normalized voltage-output signals from the SIN and COS windings, divided by the reference voltage. Traditional reference voltages are anywhere in the 1- to 26-V range, and the output frequency range is 800 Hz to 5 kHz.[1]

Figure 2. Normalized output voltages of SIN and COS windings



It is now possible to determine the requirements for the appropriate signal-chain devices. The signal chain needs to be bipolar because to the signal swings below ground (Figure 2). It must simultaneously sample two channels, convert up to 5-kHz signals, and supply AC voltage to the resolver for the reference winding. The optimum solution is to implement two delta-sigma modulators, one for each channel. The delta-sigma modulators sample at very high frequencies (in the 10- to 20-MHz range), so the delta-sigma modulated outputs are averaged out and filtered to achieve an acceptable resolution.

Figure 3. Simplified block diagram for resolver control-loop system



For the reference voltage or AC-excitation source, a pulse-width modulation (PWM) signal applied directly to the resolver is preferred. TI has a recommended solution for this kind of implementation. A data converter such as the ADS1205 or ADS1209 is preferred for the delta-sigma modulator because both are designed for direct interface to the resolver's SIN and COS windings. The data converter also interfaces to a four-channel sinc filter/integrator with a PWM signal generator output for the reference winding, for example the AMC1210. Finally, a digital signal processor (DSP) or real-time controller is needed to handle all the various signals in addition to the motor control system. One such option is the C28x-based C2000™ Piccolo™ F2806x microcontroller from TI. Figure 3 illustrates a typical signal-chain solution.

Conclusively, a resolver is a very robust position sensor for a control system that offers high accuracy possibilities and long operating life. A disadvantage of the resolver is its maximum rotational speed. Because resolver signal frequencies tend to be less than 5 kHz, motor speeds need to be less than 5,000 revolutions per minute.

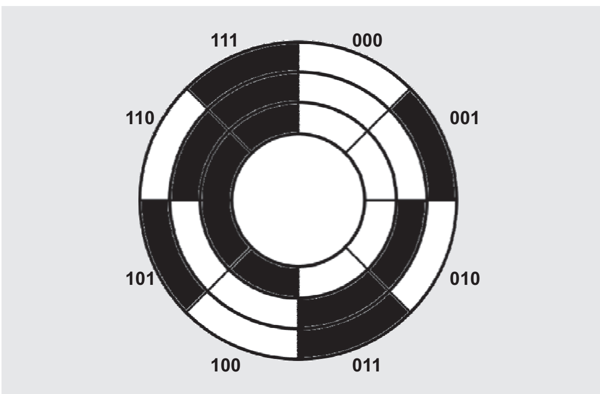
Encoder

As with the resolver scenario, before going into the signal-chain implementation, is important to understand the physical and signal-output characteristics of encoders. Typically there are two types of encoders: linear and rotary. Linear encoders are used for items moving only in a single dimension or direction, and convert the linear position into an electronic signal. These often are used in conjunction with actuators. Rotary encoders are used for items moving around an axis, and convert the rotary positions or angles into electronic signals. Since rotary encoders are used with motors (as motors rotate along an axis) linear encoders are not covered in this article.

To understand the principle behind a rotary encoder, first consider a basic optical rotary encoder. An optical encoder has a disk with specific patterns mounted to the motor shaft. The patterns on the disk either blocks light or allows it to pass through . Thus, a light-emitting transmitter is used along with a photocel receiver. The receiver signal output can be correlated to the motor's rotary position.

There are three common types of rotary encoders: absolute position value, incremental TTL signal, and incremental sinusoidal signal. For absolute position value rotary encoders, the pattern on the disk is broken up into a very specific pattern based on its location. For example, if the absolute position encoder has a 3-bit digital output, it would have eight different patterns, evenly spaced (Figure 4). Since this is on a disk and is evenly spaced out, the spacing between each pattern is 360°/8 = 45°. Now the position of the rotary motor is known to be within 45° for a 3-bit absolute position value rotary encoder.

Figure 4. Example of 3-bit absolute position value rotary encoder



The output of the absolute position value rotary encoder is already optimized for digital interfaces, so an analog signal chain is not required.

For the incremental TTL rotary encoder, the pattern on the disk outputs a digital high or low, which is a TTL signal. As shown in Figure 5, the TTL-output disk pattern is relatively simple compared to the absolute position value rotary encoder, because it needs to represent only one digital high or digital low. In addition to the TTL signal there also is a reference mark which is essential in determining the motor's current rotary position. The reference mark can be thought of as angle 0°. Thus, simply counting the digital pulses can determine the exact rotary position of the motor.

Figure 5. Example of incremental TTL rotary encoder

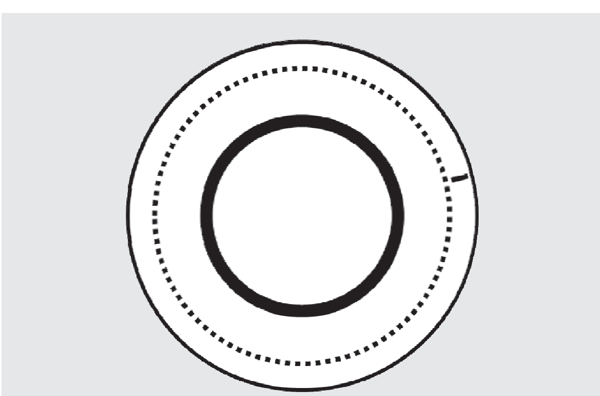
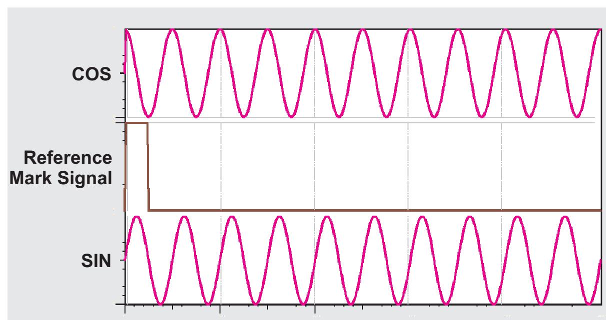


Figure 5 illustrates multiple periods in one revolution of the motor shaft. Encoder manufacturers offer incremental TTL rotary encoders (and incremental sinusoidal rotary encoders) with 50 to 5,000 periods per revolution. As with absolute position value rotary encoders, the output is already in a digital format, so no analog signal chain is required.

For the incremental sinusoidal rotary encoder, the output and disk pattern is quite similar to the TTL-signal encoder. Instead of a digital output, the output is what the name implies: a sine wave output. Actually, it has both sine and cosine outputs along with the reference mark signal as shown in Figure 6. These outputs are all analog, so an analog signal-chain solution is required.

Figure 6. Modeled output of incremental sinusoidal rotary encoder



Similar to the incremental TTL output, there are multiple signal periods in one revolution. For example, if the encoder with 4,096 periods in one revolution is selected and attached to a motor spinning at 6,000 revolutions per minute, the resulting sine and cosine signal frequencies can be calculated.

$$f_{\text{sine/cosine}} = \frac{\text{Periods}}{\text{Revolution}} \times \frac{\text{Revolutions}}{\text{Minute}} \times \frac{1\text{ Minute}}{60\text{ Seconds}}$$

$$= \frac{4{,}096}{1} \times \frac{6{,}000}{1} \times \frac{1}{60} = 409.6\,\text{kHz}$$

A signal-chain solution needs to have a bandwidth of at least 410 kHz for this example. Since this is a closed-loop control system, latency must be kept to a minimum or completely eliminated. Traditionally, the encoder output is 1 $V_{P\text{-}P}$, and the sine and cosine output signals are differential.

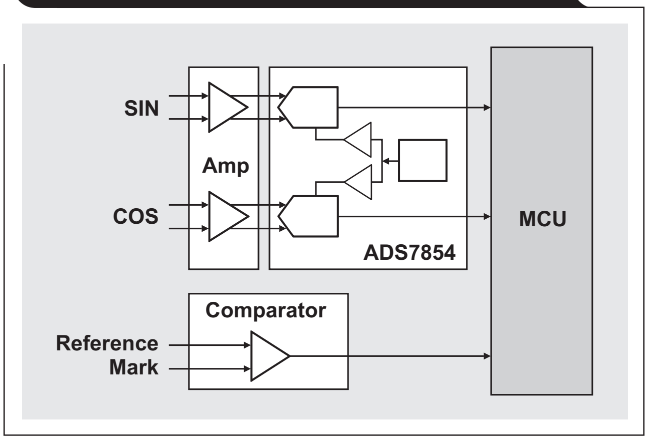
The typical requirements for the analog signal-chain solution are:

- Two simultaneously-sampling analog-to-digital converters (ADCs): One for sine and one for cosine outputs.
- No system latency: More than 400 kHz of bandwidth are needed, thus an ADC must handle 800 kSPS per channel minimum.

- 1-V_{P-P} differential input with a full-scale range of around 1 V to optimize the ADC's full-scale range, or amplification of the input signal to the ADC's full-scale range.
- A comparator for the reference-mark signal.

The optimum solution from TI is the ADS7854 family of successive-approximation register (SAR) ADCs (Figure 7). With two simultaneously-sampling channels, an internal reference and 1-MSPS per channel output data rate, this SAR-ADC meets the specified requirements. It can be used with a comparator and a fully-differential amplifier to drive the ADC.

Figure 7. Simplified signal-chain solution to incremental sinusoidal rotary encoder



Because the ADS7854 is a 14-bit ADC, and if the sinusoidal incremental rotary encoder has 4,096 periods in one revolution, the total number of measuring steps can be calculated.

$$\text{Number of Steps} = 2^{(\text{ADC Resolution})} \times \frac{\text{Periods}}{\text{Revoluion}}$$
$$= 2^{14} \times 4{,}096 = 16{,}384 \times 4{,}096$$
$$= 67{,}108{,}864.$$

This gives the designer 26-bits of resolution when implementing this approach, or accuracy of the rotary position to within 5.36×10^{-6} degrees.

Conclusion

There are two common implementations of rotation/position sensors in a motor-control feedback path: a resolver and an encoder. The feedback path and output signal characteristics of several control systems were evaluated from the analog signal-chain perspective for either a resolver or encoder to ensure signal integrity and optimum performance.

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Extract maximum power from the supply when charging a battery

By Jing Ye, *Systems Engineer, High-Power Charging*
Jeff Falin, *Applications Engineer, Wireless and Low-Power Charging*
KK Rushil, *Field Applications Engineer*

Introduction

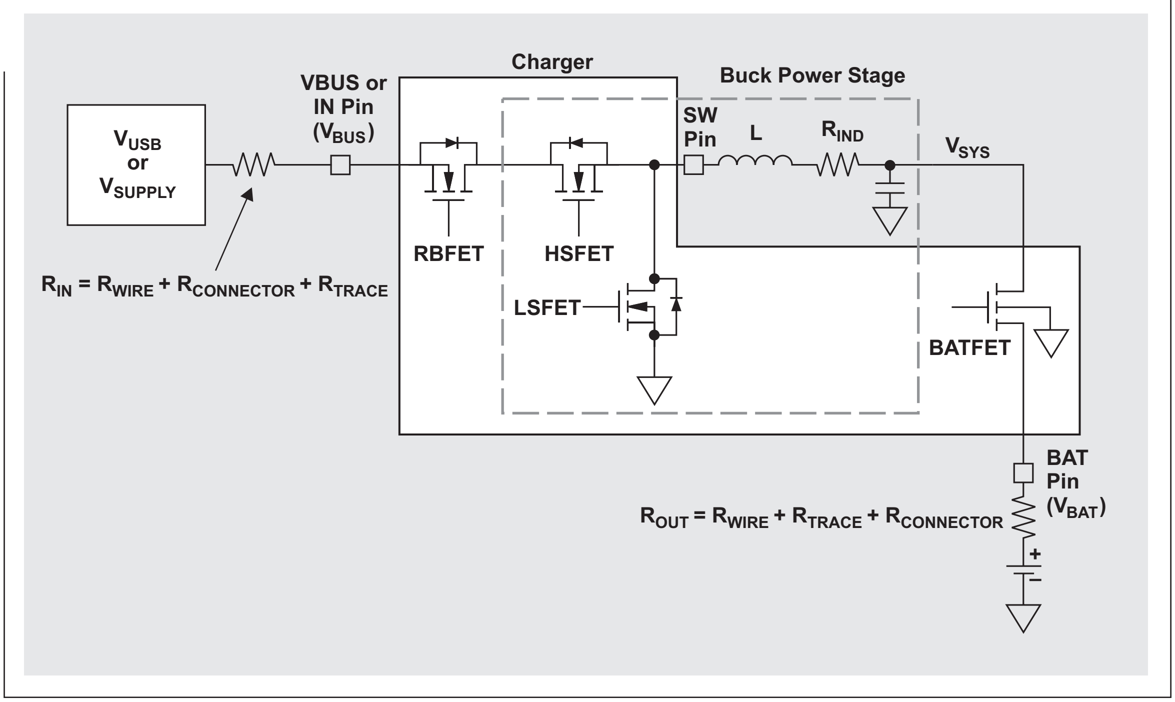
Designers of rechargeable battery-powered equipment want a charger that minimizes charge time with maximum charge current by maximizing the power taken from the supply without collapsing the supply. Resistances between the supply and the battery present a challenge. This article explains how to design the charging circuit to achieve the maximum power from the adapter despite the undesired resistances between the supply and battery.

General operation of a switch-mode charger

Figure 1 contains a circuit model of the buck converter-based charger that shows all of the non-ideal resistances, including the inductor's DC resistance (R_{IND}).

The input supply voltage to the charger IC at its VBUS or IN pin is from a typical USB port or a wall adapter. For this article, voltage at this pin is V_{BUS}. This model will be used to derive the minimum supply voltage for a given battery regulation threshold.

Figure 1. Switching charger model with resistances



Review of Li-Ion charger operation

As shown in Figure 2, the charger works in three main phases of operation, depending on the battery voltage:

1. Low battery voltage signifies a deeply discharged battery. Hence, it must be charged by a low value of current until it is brought to the threshold value, V_{PRECHG}. This is known as precharge phase.
2. Once the battery voltage increases to a certain threshold (V_{PRECHG}), the prescribed maximum charge current is allowed to flow. This current is maintained by a regulation loop known as the current-regulation/constant-current phase.
3. After the battery voltage increases to the set regulation voltage and the charge current has tapered down, the battery is fully charged. While the charge current is tapering down, the charger operates in voltage-regulation/constant-voltage phase. The typical regulation voltage is 4.2 V for Lithium-Ion (Li-Ion) cells.

For fastest charge time, the charger must provide the maximum charge current for which it has been set, until V_{BAT} = 4.2 V.

To determine the minimum value of the input voltage (V_{BUS_MIN}) permissible, the designer must consider the following:

1. Operation headroom between V_{BUS} and V_{BAT} to reach a target charge current
2. Switching regulator's maximum duty cycle

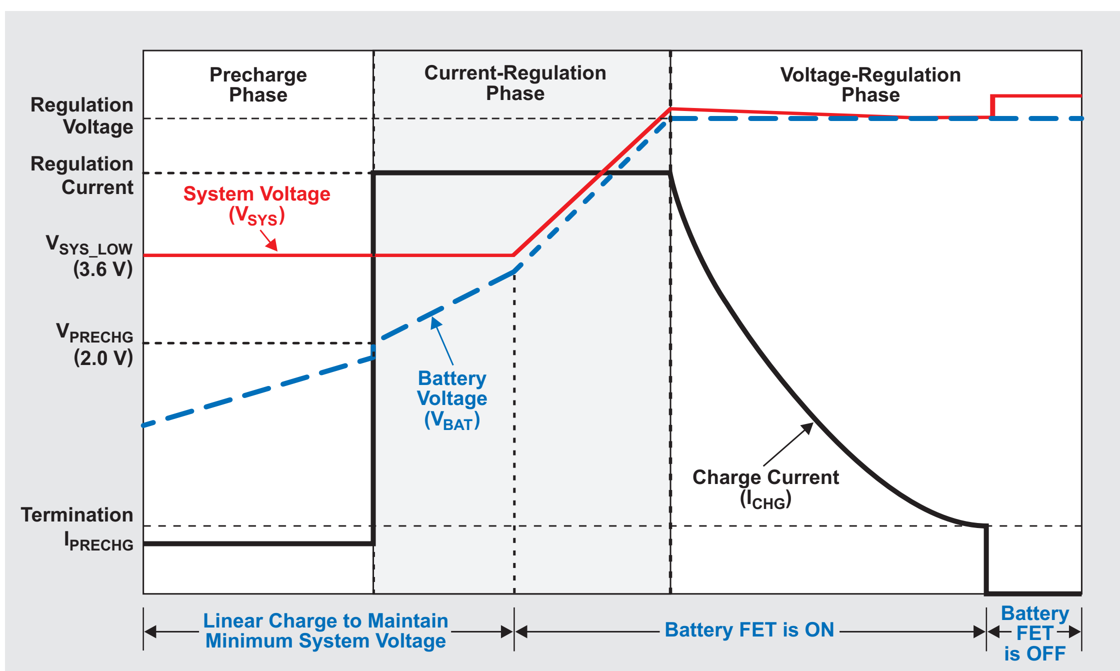
Operation headroom

The resistance in the MOSFETs and the inductor generates voltage drop as current flows. If the voltage difference between V_{BUS} and V_{BAT} is too small, the target charge current cannot be achieved. For example, if V_{BUS} is 4.3 V, V_{BAT} is 4.2 V and total resistance from BUS input to battery is 150 mW, the maximum current to the battery is 660 mA.

Switching regulator maximum duty cycle

Realistically, no high-side NMOS buck converter can reach 100% duty cycle. There is always dead time to avoid shoot-through during HSFET/LSFET turn-on/turn-off. If the duty cycle exceeds the maximum value, the switching regulator will skip some LSFET turn-on pulses to maintain average output current/voltage.

Figure 2. Charge profile for the BQ2419x/25x/26x/29x charger

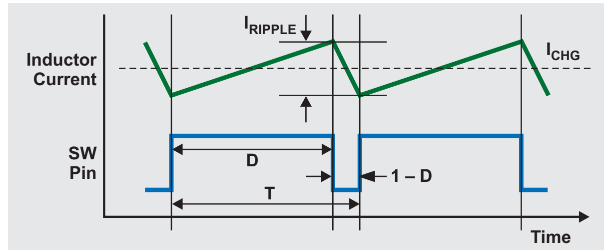


Calculating V_{BUS_MIN} threshold

The V_{BUS_MIN} threshold is the minimum BUS pin voltage required to support the target maximum charge current and keep the duty cycle below the buck converter's maximum duty cycle. Figure 3 shows the inductor current and switch-node voltage of a buck converter operating in the continuous-conduction mode (CCM). V_{BUS} can be derived as follows via ripple-current calculations for the inductor.

$$I_{RIPPLE} = \frac{\Delta V \times \Delta T}{L} \quad (1)$$

Figure 3. Inductor current versus operation duty cycle in CCM



On the inductor current rising edge:

$$I_{RIPPLE} = \frac{\left[V_{BUS} - I_{CHG} \times (R_{RBFET} + R_{HSFET}) - I_{CHG} \times (R_{IND} + R_{BATFET}) - V_{BAT}\right] \times D \times T}{L}. \quad (2)$$

On the inductor current falling edge:

$$I_{RIPPLE} = \frac{\left[V_{BAT} - I_{CHG} \times (R_{IND} + R_{BATFET}) - I_{CHG} \times R_{LSFET}\right] \times (1-D) \times T}{L}. \quad (3)$$

Since the ripple current is the same, the V_{BUS} equation can be derived.

$$V_{BUS} = \frac{1}{D} V_{BAT} + I_{CHG} \times (R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) - \frac{1-D}{D} \times I_{CHG} \times (R_{BATFET} + R_{IND} + R_{LSFET}) \quad (4)$$

Equation 4 can be simplified with a few assumptions:

- With L = 2.2 µH, the ripple current at 96% duty cycle is less than 300 mA. (One is considered as average current.)
- With maximum duty cycle of 96%, (1 – D) / D is only 4.2% compared to the second item in the equation. Therefore, the third item can be ignored.

The V_{BUS_MIN} threshold is the V_{BUS} voltage at maximum duty cycle.

$$V_{BUS\_MIN} = \frac{V_{BAT}}{D_{MAX}} + I_{CHG} \times (R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) \quad (5)$$

If V_{BUS} falls below calculated V_{BUS_MIN} threshold, then the battery will not fully charge.

Minimum USB supply voltage

This section shows how the input voltage to the charger can fall below the permissible value when USB adapters are used due to input line resistance. The USB specification states that the output to the device from a low-power port can be as low as 4.1 V under full load, after passing through all hubs and cables.

Assume that the input supply in Figure 1 is a USB port providing V_{USB} of 5 V with zero resistance in series. R_{IN} is the lumped resistance of the cable, connector and PCB trace. The charger is modeled as an ideal buck converter that can reach 100% duty cycle.

The input voltage (V_{BUS}) at the charger must be above the battery charging regulation threshold V_{BATREG} (typically 4.2 V). Assume that the minimum to which V_{USB} falls is 4.75 V.

$$V_{BUS} = V_{USB\_MIN} - I_{USB\_MAX} \times R_{IN} > V_{BATREG} \quad (6)$$

With resistance from the USB supply to BUS pin of R_{IN} = 400 mΩ, Table 1 shows the minimum V_{BUS} voltage from USB2.0 port and USB 1.5-A adapter.

Table 1. USB Supply Comparison

	V_{USB_MIN}	I_{USB_MAX}	V_{BUS}	BELOW V_{BUS_MIN}?
USB 2.0	4.75 V	0.5 A	4.55 V	No
USB 1.5-A Adapter	4.75 V	1.5 A	4.15 V	Yes

At maximum duty cycle, V_{BUS} is close to V_{BAT}, so $I_{USB} \approx I_{CHG}$. Equation 5 can now be expanded to determine the minimum input supply voltage for a given charge current.

$$V_{SUPPLY\_MIN} = \frac{V_{BAT}}{D_{MAX}} + I_{CHG} \times (R_{IN} + R_{RBFET} + R_{HSFET} + R_{IND} + R_{BATFET}) \quad (7)$$

Equation 7 can be used to determine how low to make the cable resistance and connector (for instance, select a higher quality cable and connector), or how wide/thick to make the PCB trace to avoid excessive voltage drop at the charger's BUS pin. This maximizes the adapter's power for charging the battery.

Input voltage-based dynamic power management (V_{IN}-DPM)

If multiple adapters and/or cables and/or connectors are expected to be used, it may be difficult to design for all line-resistance scenarios. A charger with V_{IN}-DPM prevents the input voltage from crashing regardless of input line resistance.

What is V_{IN}-DPM?

V_{IN}-DPM is an analog loop included in many TI chargers. The purpose of the loop is to extract the maximum amount of current available from the supply without crashing the adapter, i.e., the input current (and therefore the resulting charge current) is limited in order to maintain supply voltage at V_{IN}-DPM. This feature can be used when a USB port is one of the input power sources.

Operation without V_{IN}-DPM

Consider using a charger without the V_{IN}-DPM protection as shown in Figure 4. As the system load current and battery charge current increase, the input current also increases. Hence, the drop across the supply resistance increases. The voltage seen at the charger's input pin is less than the rated output voltage offered by the supply. Also, the supply (voltage source) has a compliance limit on the amount of current it can produce. When a load current is drawn such that the input current required to maintain the sum of charge current and load current is beyond the capability of the supply, the input voltage starts to fall because the input capacitor discharges due to the high current demanded. When the input voltage hits the undervoltage threshold, the charger turns off. During this off time, the input voltage recovers as the input capacitor recharges. Once it rises above the UVLO, charging begins again. Once the charger turns on, the same cycle repeats, resulting in the non-ideal on/off pulsing in the charge current.

Benefits of V_{IN}-DPM

A charger with the V_{IN}-DPM feature prevents the non-ideal pulsing of charge current by limiting input current. Specifically, as the input voltage reduces and hits the set V_{IN}-DPM threshold, the V_{IN}-DPM function activates to reduce the input current to a smaller value. This prevents the input voltage from crashing to the undervoltage point.

Adapters typically supply currents between 100 mA to several amperes, and the latest USB ports can supply up to 1.5 A and higher. When using a charger with V_{IN}-DPM, portable-equipment manufacturers can optimize the charger for adapters and USB ports having a certain output power limit, such as a current limit. V_{IN}-DPM allows operation with other lower cost adapters, USB ports and/or the cables in between. For example, a smartphone with a charger having V_{IN}-DPM would be able to extract

Figure 4. Non-ideal pulse charging by charger with high input line resistance and no V_{IN}-DPM

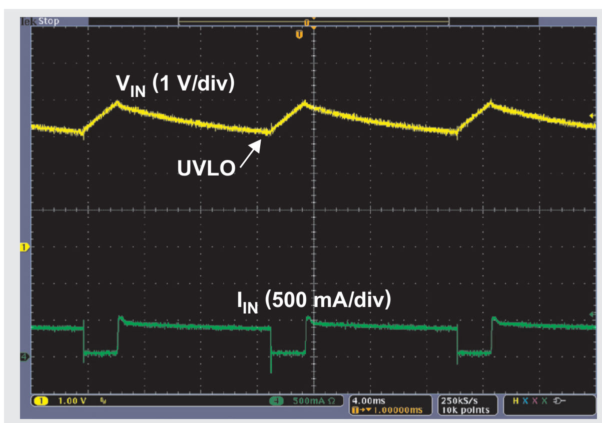
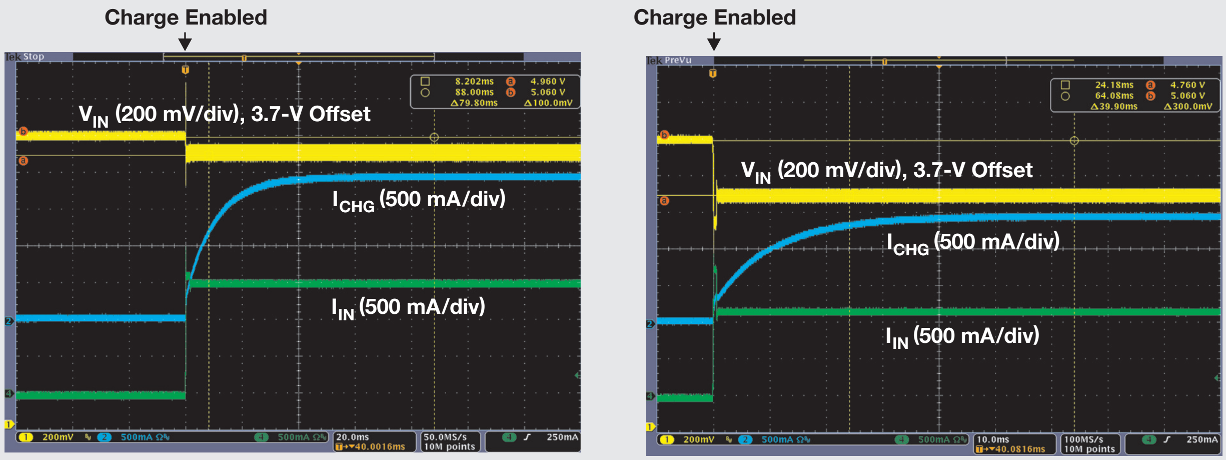


Figure 5. Example of a battery charger without and with V_{IN}-DPM engaged



(a) $R_{IN} = 50\ m\Omega$ (b) $R_{IN} = 250\ m\Omega$

maximum power from a 1.5-A USB port without collapsing the port, even if a low-cost, highly-resistive USB charging cable is used. Figure 5 shows the effects of two different input resistances from the power supply to the IC. The evaluation circuit was a battery charger like the bq24192, bq24250, bq24260 or bq24295, that was configured for 1.5-A input current limit, 2.0-A charge current and 4.76-V V_{IN}-DPM threshold.

In both cases, charging continues and the adapter does not crash. However, in Figure 5(b), the V_{IN}-DPM circuit reduces the input current limit in response to the voltage drop across the series resistance. With reduced input current, the charger will reduce first the charge current and then the system load current.

Conclusion

Resistances between the supply and charger can prevent the charger from pulling the maximum power from its supply without collapsing the supply and hitting the charger's undervoltage lockout. An equation for determining the minimum supply voltage required for a charger to provide the maximum charge current from given supply adapter was developed. Additionally, the V_{IN}-DPM feature allows the use of a variety of adapters and/or power connections without fear of collapsing the adapter voltage as it dynamically reduces the charger's input current limit.

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Adapting Qi-compliant wireless-power solutions to low-power wearable products

By Bill Johns, *Senior Applications Engineer*
Kalyan Siddabattula, *System Engineer*
Upal Sengupta, *Applications & Marketing Manager*

Introduction

A large number of low-power wearable devices such as smart watches, fitness wrist bands and headphones have been introduced to the market (Figure 1). This new family of electronic products is expected to grow and expand rapidly over the next few years. These devices are typically small and thin, with varying form factors and industrial design. Battery sizes might range from 100- to 300-mAh capacity, which determines the required charge rates.

The plug-and-jack style or micro-USB types of connectors have been the traditional way to charge such devices. But even these relatively small connectors are now too large for some of the new ultra-thin wearable applications. Connector contamination is an even greater problem due to the outdoor wearable environment.

Wireless charging is a solution to these problems and offers additional opportunities to designers. Existing semiconductor devices used for the Qi standard established by the Wireless Power Consortium (WPC) can be easily adapted for this lower-power application. The technology uses two planar coils to transfer power though a sealed case. For low-power wearable devices, a small, thin low-power receiver coil easily could fit into the back of the case or wristband area. Qi-compliant devices are a mature solution that can shorten development time, and the products are supported by the existing WPC infrastructure.

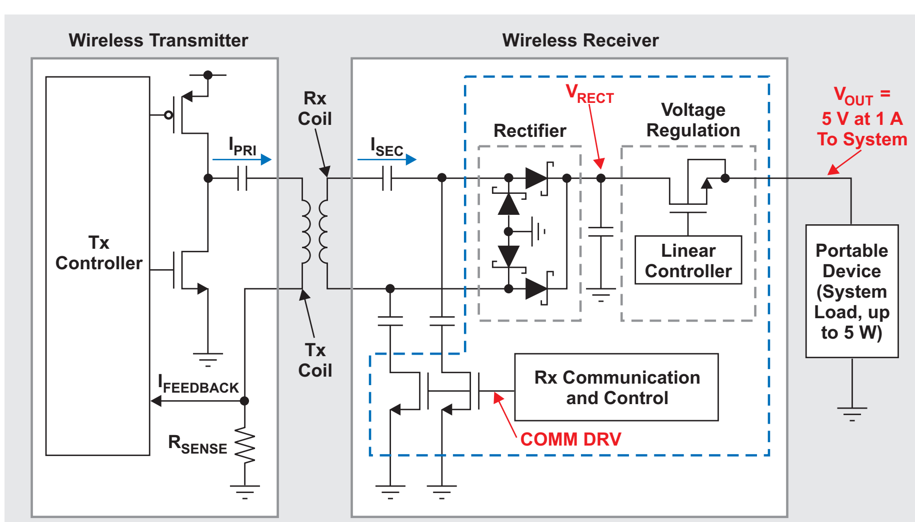
Figure 1. Smart watch with wireless charging

Used with permission from Secret Labs. LLC

Qi-compliant wireless-power system

The typical wireless power system (Figure 2) has a receiver (Rx) in the portable device that provides energy to charge the battery. The transmitter (Tx) is located in a fixed base and is connected to a wall power supply. Input power to the transmitter is converted to AC, then magnetically coupled though the transmitter coil to the receiver coil when they are in close proximity. Output from the receiver is typically 5 V at up to 1 A, which provides input power to a battery charger IC inside the portable device.

Figure 2. Block diagram of a Qi-compliant system



Transmitter operation in this system is controlled by the receiver chip using feedback in the form of digital communications packets sent back over the same magnetic coupling path. The Qi-compliant receiver communicates with the transmitter using load modulation to send information in data packets across the two coils. The transmitter-coil voltage and current are modulated at a 2-kHz rate that is decoded by the transmitter and used for control. The receiver can send several types of packets to the transmitter for control and information purposes. Also, a loss of communications terminates any power transfer.

The Qi-standard's *identification-and-configuration* command packets are very useful to assure that power is only transferred to the correct device, avoiding potentially hazardous situations. *Charge-complete* and *end-power-transfer* packets are also useful commands that stop power transfer when the battery is charged, or when other conditions require that power transfer be stopped.[1] These features assure safe power transfer between the transmitter and receiver using an existing, well-known standard.

Low-power wireless systems

An available Qi-compliant receiver and transmitter can be optimized for a low-power wireless system by carefully tailoring the coil sizes and external component values to match the smaller application. Coils for both the transmitter and receiver can be reduced in size to fit the smaller form factor. Power-section components, in particular for the transmitter, can have reduced power specifications.

The typical WPC-1.1, Qi-compliant system supports up to 5-W output loads, typically 5 V at 1 A. A low-power system for a wearable-device application, on the other hand, might have output power in the range of 5 V at 100 to 250 mA.

Most Qi-compliant features can be used without impact on size or performance. Foreign-object detection (FOD) is an optional feature that protects against power transfer to stray metal objects in the charging area. In a low-power system with FOD, total output power is reduced by more than 50%. Along with reduced charging area, the possibility of introducing an object into the field that will heat up enough to present a problem is greatly reduced. The criticality of the FOD function may depend primarily on the mechanical design of the charging pad or charging cradle for a wearable device. Table 1 summarizes some of the key functions available when using the WPC-1.1 Qi standard that may or may not be required in a customized wearable application.

Table 1. Qi-compliant standard versus wearable solution

FEATURE	QI-COMPLIANT?	WEARABLE?
Identify Rx before power transfer	Yes	Yes
Stop power transfer on Rx command	Yes	Yes
Charge complete indications	Yes	Yes
Foreign object detection	Yes	Optional
Power transfer up to 5 W	Yes	Optional
Inter-operability with other devices	Yes	Optional

Low-power system coils

Coils can be reduced in size to a point, but must still transfer power and communicate with the transmitter. Typical coil construction is a round planar coil made of copper wire on a shield. Alternate configurations are PCB or flex-circuit coils. Typically, these alternates could have higher DC resistance (lower efficiency) but can be very thin, a desirable feature for small, low-power applications. The shield prevents AC fields from entering the electronics and battery, which also can improve coil performance.

Assuming that the Rx and Tx coils are aligned in the x-y plane, there are two key factors that determine the coupling factor, k. The first is coil-to-coil (z) distance, and the second is the ratio of diameters of the two coils. The best coupling (highest k) results when the coils are closer together and matched in diameter.[2] To ensure close x-y alignment from the start, the mechanical design of the charging base or cradle for a wearable device should include a physical means of aiding proper placement of the device in the cradle. Because the receiver coils are very small in this application, a slight misalignment between the Rx and Tx coils can result in a significant reduction in coupling factor and very poor power-transfer efficiency.

In a coupled-inductor system such as WPC/Qi, the coupling coefficient (k) between the primary and secondary coil generally is in the range of 0.5 to 0.7. A typical transformer can have a much higher k, such as 0.99. When the coupling factor is low, a higher inductance value is required on the secondary (receiver) side to ensure that the output power demands can be met. As a result, small low-power devices that may have low coupling actually require a larger secondary inductance than the standard 5-W designs.[3] A higher-inductance receiver coil with more turns and larger shield may be needed to achieve the required voltage gain.

Coil design

Design trade-offs of the receiver coil size include the wire diameter, shield size and thickness. Coil DC-resistance shows up as a reduction in receiver efficiency. The receiver coil design requires a specific number of turns to achieve the desired inductance. As previously noted, the required inductance of a small coil will be higher than a large coil due to a decrease in coupling factor. As the number of turns increases to achieve the higher inductance value in a smaller space, the wire diameter decreases. The combined effect of smaller wires and more turns will drive the DC-resistance higher and lower efficiency.

The shield provides a low-impedance path for the magnetic flux and increases coil inductance. Also the shield prevents the AC field from entering the battery and surrounding metal in the receiver. A larger and thicker shield is better because thinner shields run the risk of saturation in high-flux fields. Transmitter coil designs have fewer physical restrictions. The coil can be larger and have lower inductance.

A typical coil used for standard 5-W WPC applications is the A11 coil type. This circular coil is approximately 50-mm in diameter and has a thick ferrite shield behind it. While this coil has been tested in a wide range of applications with many types of receivers, it works best for the higher power levels (3 to 5 W). For lower-power and reduced-range receivers, many coil dimensions can be reduced.

Typical inductance of the A11 coil is 6.3 µH. This value should be maintained for best performance. Wire diameter can be reduced to allow a smaller coil size, however, this increases DC-resistance losses. Further size reduction can be achieved with a reduction in shield thickness. Several types of shields are available that provide good performance.

Tests with a 30-mm round transmitter coil have been conducted with good results (Figure 3). Smaller solutions are possible, but the designer must take care that the DC resistance is not increased significantly. In the case of the resonant-converter architecture used in most WPC transmitters, current flows in the primary coil even at minimal loads. To avoid excessive power loss, the DC resistance of the Tx coil must be as low as is practically possible, given the size constraints of the product.

Low-power receiver

The bq51003 is one device in the TI bq51xxx family of wireless-power receivers that is adapted specifically for lower-power applications. The key change in the device is optimizing the behavior of a few features for lower output current.

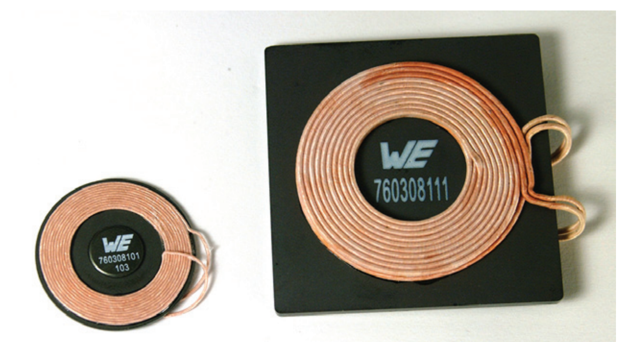
This family of devices features Dynamic Rectifier Control™ to improve load-transient behavior. The Qi standard has a relatively slow global feedback loop and may require up to 100 ms to change the operating point. This means that a load-step can reduce output voltage and result in system resets. To provide enough voltage to operate though a transient, the V_{RECT} operating point is set high at low loads. This feature helps with load-step, but reduces light-load efficiency. To solve this problem, Dynamic Efficiency Scaling™ is used to tailor the light-load voltage to maximum output load. Maximum output current is set using a resistor.

Table 2. Dynamic Rectifier Control for wireless receiver (bq51003)

OUTPUT CURRENT PERCENTAGE	R_{ILIM} = 1116 Ω I_{MAX} = 250 mA	R_{ILIM} = 488 Ω I_{MAX} = 500 mA	V_{RECT}
0 to 10%	0 to 25 mA	0 to 50 mA	7.08 V
10 to 20%	25 to 50 mA	50 to 100 mA	6.28 V
20 to 40%	50 to 100 mA	100 to 200 mA	5.53 V
>40%	>100 mA	>200 mA	5.11 V

Due to the reduced PCB area for power dissipation, thermal paths also should be taken into consideration. Since the typical application requires charging a small battery with reduced charge current, power dissipation can be managed.

Figure 3. Standard transceiver coil and 30-mm, low-power coil



As mentioned previously, the bq51003 (and other constant-voltage output receivers such as bq51013B) work in tandem with a second IC to regulate and manage current flow to a Li-Ion battery. These batteries require a precise constant-current/constant-voltage charge-control profile, which can be implemented using a device such as the bq24232 (Figure 4). For low-power applications, a simple low-cost linear charger is usually the best choice. One key factor in deciding the charger device is to verify that it can control the low charge-current levels needed by the small batteries used in wearable devices. The bq24232 can regulate down to 25-mA constant-current levels, if needed, and has been implemented in applications with small battery sizes. Refer to the bq24232 data sheet for additional details on the charge control functionality required for Li-Ion batteries.

Low-power transmitter

For the typical 5-W application, there are many Qi transmitter types available with a wide range of features. The bq50xxx family supports 5-W or greater receiver output power. The bq500211 is a good starting point for low-power applications. The standard EVM kits are provided with the single-coil 5-V input, A11 type of transmitter coil. However, as discussed previously, this coil can be replaced with a smaller component for the lower-power wearable applications. This unit has the option to operate from a USB port or low-power 5-V adapter. The transmitter design has the option to be small and low cost.

The bq500211 Qi-transmitter controller has an input power-limiting option. The input current to the transmitter can be limited to 500 mA, which allows operation from a

Figure 4. Wireless power receiver with battery charger for low-power application

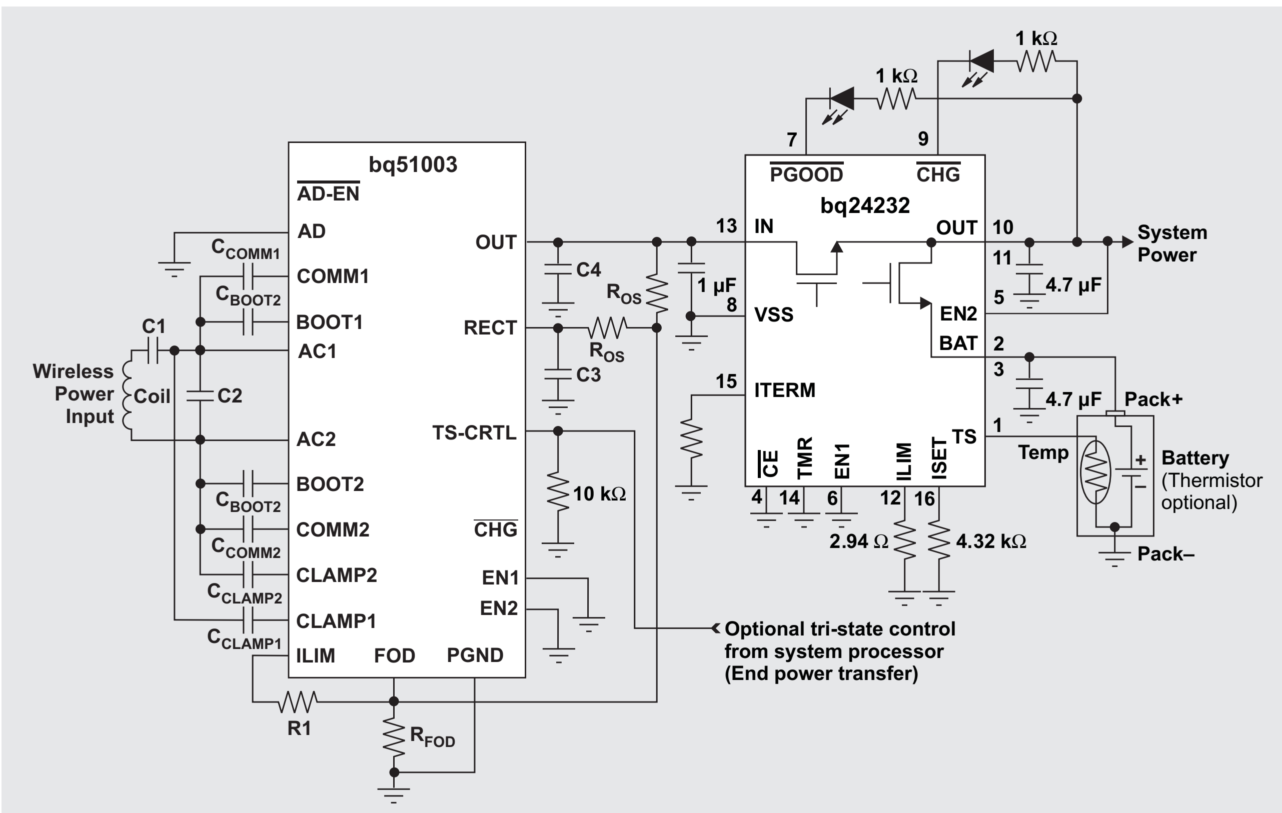
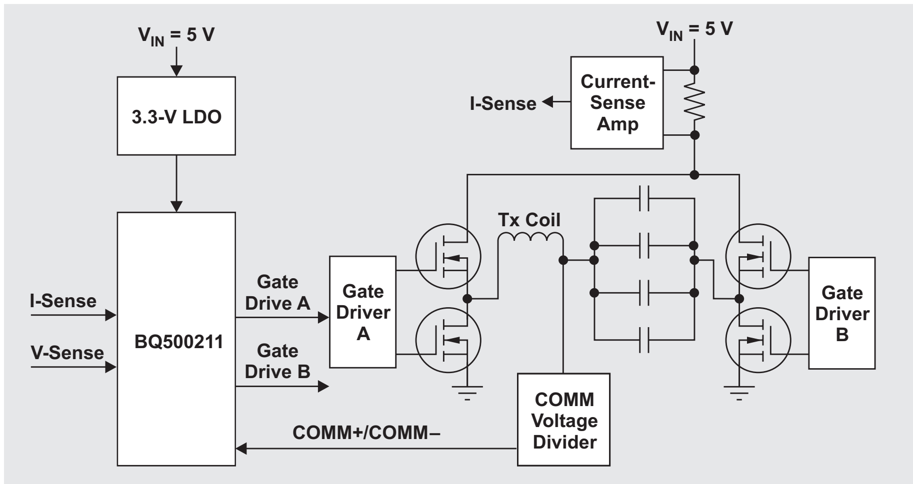


Figure 5. Low-power transmitter



USB port or small adapter. This works very well with low-power receivers with low current demand. A block diagram example is shown in Figure 5. Input current is sensed across a resistor and amplified through a current-sense amplifier. The power section uses power-stage MOSFETS with integrated drivers. But independent drivers and low-loss MOSFETS could be used to reduce cost. As discussed earlier, at lower output power, FOD protection may be optional; the circuit shown does not have the FOD feature implemented. Also, for simplicity and cost reduction, the design in Figure 5 does not show the optional circuitry for low-power standby mode. Reference 4 has more information about this design.

Conclusion

Implementing wireless inductive charging in a low-power, wearable design is possible now using existing off-the-shelf devices. Among the key factors to design a working solution in the 500- to 1500-mW power range is optimization of the magnetic components—specifically, matching the smaller-size receiver coils to correspondingly smaller transmitter coils to maintain the best coupling factor. Also important is implementation of appropriate external circuit modifications with the bq500211 transmitter and bq51003 low-power receiver to minimize system power losses.

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3. Bill Johns, Tony Antonacci and Kalyan Siddabattula. "Designing a Qi-compliant receiver coil for wireless power systems," *Analog Applications Journal* (3Q 2012). Available: www.ti.com/2q14-slyt479
4. Bill Johns, "Low Power Transmitter Reference Design, bq500211," Reference Design (April 2014). Available: www.ti.com/2q14-slua705

Related Web sites

Wireless power products:
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System telemetry: What, why and how?

By Sureena Gupta
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Introduction

There has been a recent increase in demand for telemetry in many end-equipment applications using FPGAs or ASICs. The primary market segments with the largest increase in this demand have been in the computing, communications, defense, avionics and industrial markets. This article describes what telemetry is and examines several options for implementation.

First off, what is telemetry? As referred to in this article, telemetry is the measurement, control and automatic transmission of data through a digital interface such as PMBus, I^{2}C or SPI. Why is telemetry needed in a power supply? Many end applications require voltage, current, temperature, power and several other device parameters to be monitored, and even controlled dynamically. For example, in a FPGA application with a multi-phase supply, telemetry could be used to add or shed one phase to adjust the solution for optimal performance. Other typical applications include servers, base stations, routers, defense applications, and test and measurement equipment.

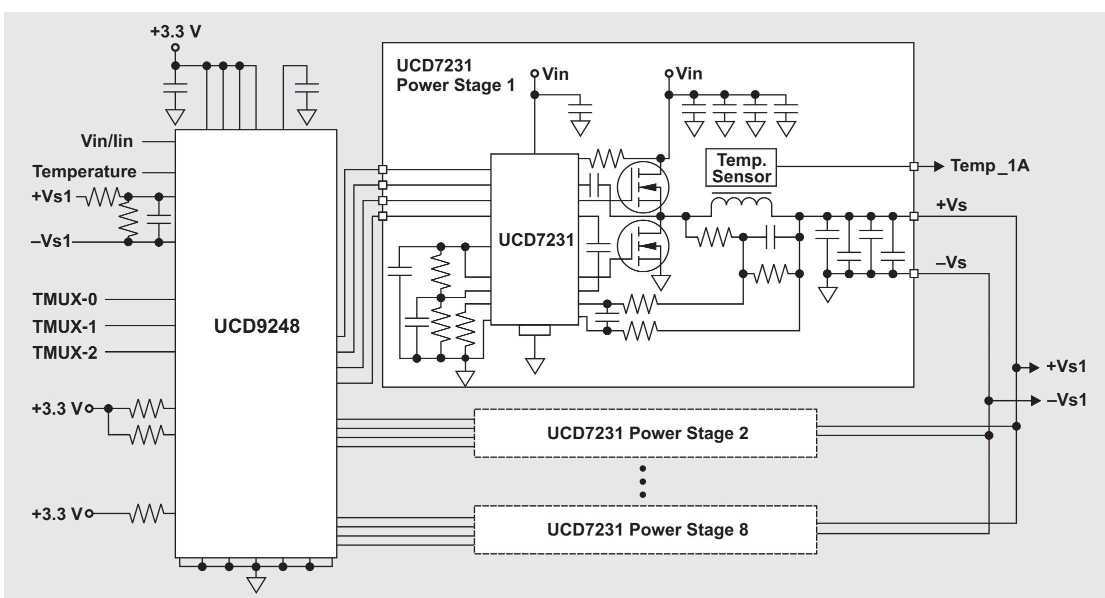
How can telemetry be applied to your applications? There are several ways to incorporate telemetry into a system that gives the designer options for maximum control, flexibility and simplicity. For a maximum level of control, a digital power controller offers the advantage of integrated data converters with a microcontroller (MCU) in addition to an extensive register set that can be used to capture and process the sensed data to manipulate the solution. If simplicity is desired for controlling the basic features, a controller with integrated PMBus (or I^{2}C, SPI, and others) telemetry functions can be a good fit for your application. An alternative to power controllers with a digital interface would be a digital sequencer or system health monitor that can be used in combination with discrete analog controllers and converters.

Option 1: Maximum level of control

Digital power controller

Digital power solutions with an built-in precision analog-to-digital converter (ADC) help measure the input and output voltage and current to capture the telemetric data. This data can be used to set the fault conditions for protection and can be logged into non-volatile memory to help understand the cause of the fault. Additional features that can be incorporated in a digital power solution includes voltage tracking, margining, sequencing, soft-start timing, current balancing and phase adding/shedding, among others. Typically, digital power solutions come with a graphical user interface (GUI) that makes it easier for the end user to configure and track real-time data measurements. An example of a digital power solution is shown in Figure 1.

Figure 1: Digital Controller used with a Fusion GUI to control the power stages



Digital power solutions provide the utmost control and flexibility in terms of scalability, monitoring real-time data, and setting up consequences to certain fault conditions. However, the solution comes with a level of complexity and higher cost. While this makes it the right solution for certain applications, it is in excess for others.

Option 2: Simplicity

PMBus converters with integrated telemetry

If the objective is to simplify the solution compared to a digital power controller, an analog power IC with an integrated digital interface is another option. This option offers the key parameters and control of telemetry, but it lacks the extensive list of controls offered by a digital power controller. Here are a few PMBus registers that are commonly found in this type of solution to store data for measurement and system control.

- Output voltage margining and adjustment
- Soft-start time
- V_{DD} undervoltage lockout (UVLO) level
- Overcurrent protection/current limit setting
- Switching frequency

This solution can be more cost-effective and less complex than a purely digital power solution. The drawback, however, is that the solution is not as flexible due to a limited register set.

Option 3: Flexibility

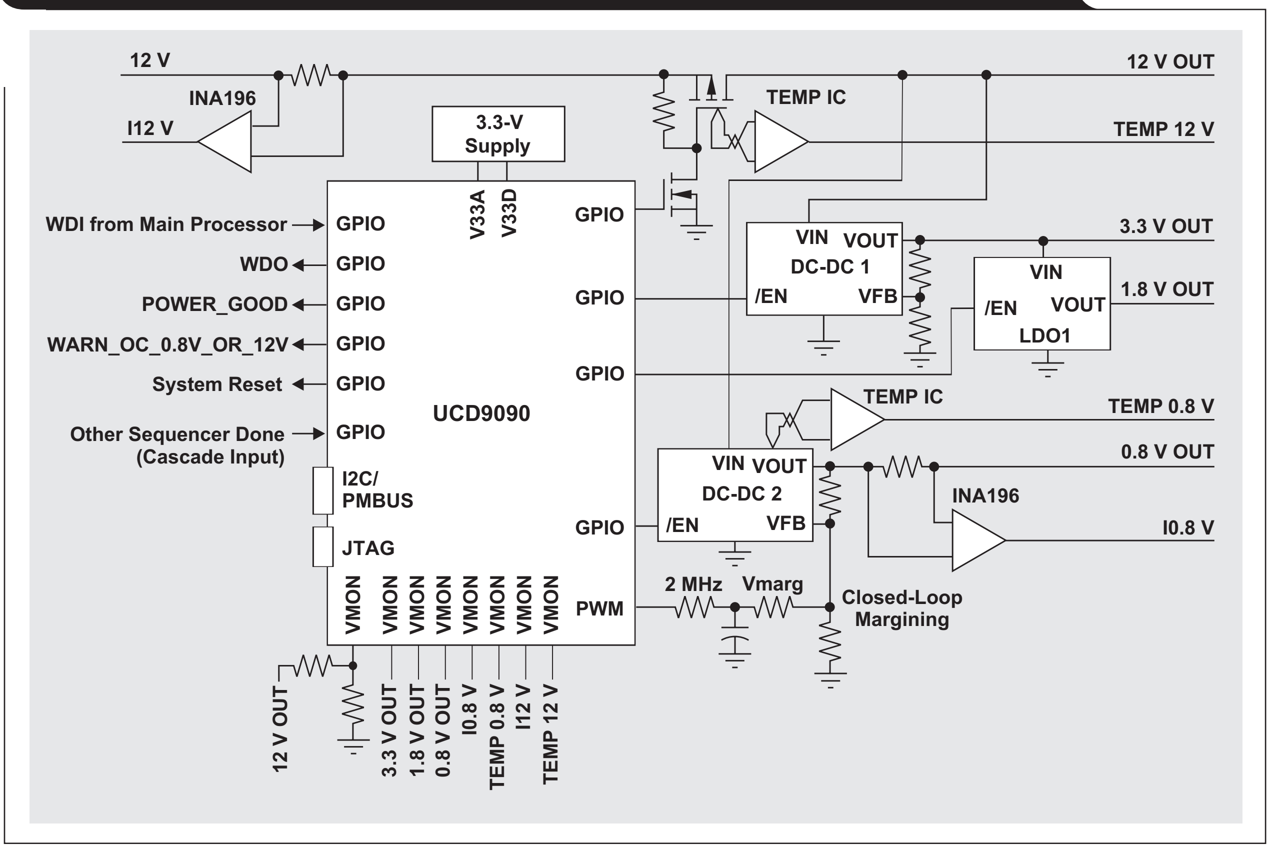
External digital-system health monitor + current sensor + temperature sensor

Another option for adding telemetry to a system is the addion of external ICs, such as a digital-system health monitor with high-precision current sensors and temperature sensors. This option provides the flexibility to use any power management IC in the industry (with or without digital interface). It also can be paired with these external ICs to provide telemetry.

A digital-system health monitor is an IC that includes rail sequencing, margining, UVLO, overvoltage protection (OVP), and a digital-communication interface. It captures and logs data that can be utilized for controlling the fault conditions and other system controls. If current and temperature also need to be monitored, the system health monitor can be used in conjunction with a current-sense amplifier and temperature sensor as shown in the Figure 2.

To accurately sense current, the current first must be converted to a voltage by placing a small-value, low-tolerance sense resistor in the current path. The voltage across the resistor can then be amplified through a current shunt monitor IC such as the INA196. This IC provides the necessary gain to provide an output voltage that can be sent to an ADC input of the digital health monitor and then to the FPGA.

Figure 2: System health monitor with current-sense amplifier and temperature sensor



There are some applications that require such high precision in measurements that an external high-resolution ADC is required, which comes with added cost. To save the cost of an independent ADC, power monitoring ICs (INA226) are available with an integrated precision ADC that can monitor voltage and current, calculate power and provide I²C telemetry (Figure 3).

Temperature monitoring is another common telemetry application that is similar to current monitoring. Some ICs, such as digital sequencers, are equipped with internal temperature sensors on the die to provide temperature monitoring. However, this limits temperature reading to only one point in the system; at the die. To monitor the temperatures at several points in a system, such as local to each power supply, remote temperature-monitoring ICs are available to convert temperature to voltage and provide telemetry interface.

Conclusion

There are many methods for measuring and controlling a system via telemetry. As a starting point, this article presented three options for integrating telemetry into your system. Digital power provides the utmost level of control, while an analog power solution with digital interface provides simplicity. The external system monitor provides the most flexibility in picking the right parts for the solution.

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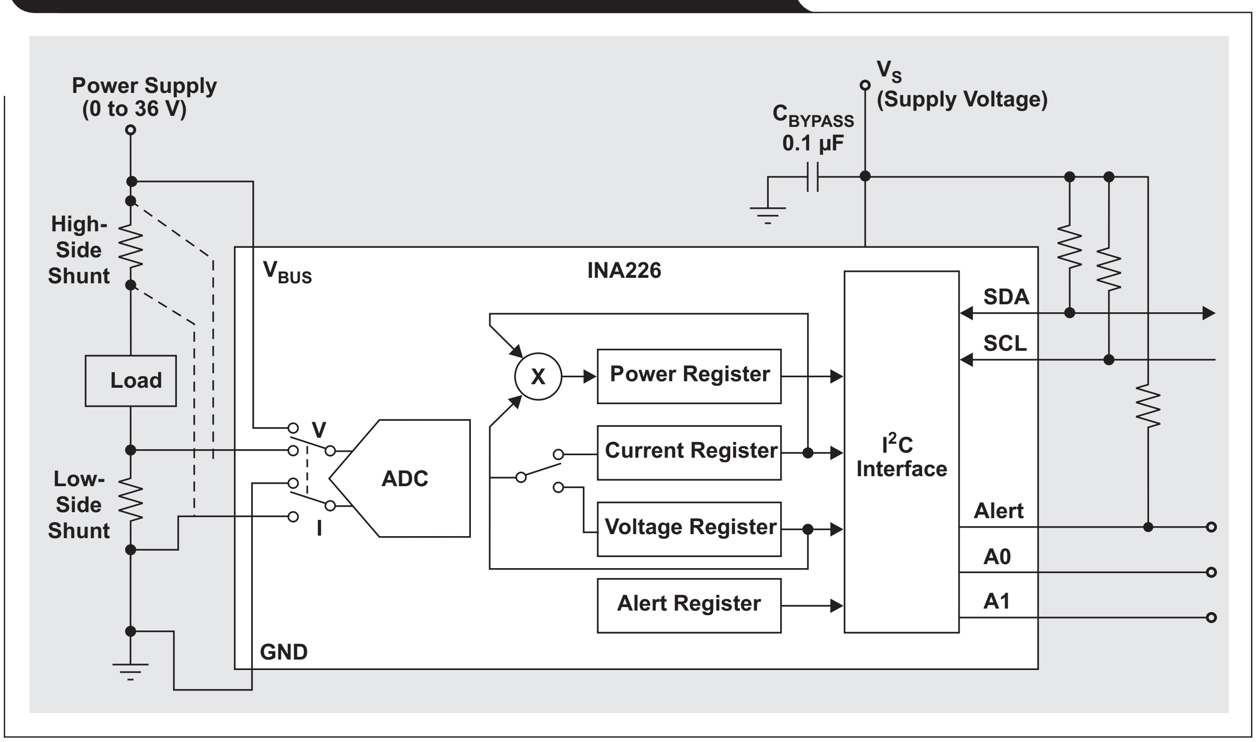
Figure 3: Power monitor with integrated ADC and telemetry



Battery-charging considerations for high-power portable devices

By Tahar Allag
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Applications Engineer

Introduction

Cell phones are a good example of how functionality and performance have both increased significantly in portable devices over the last few decades. They have become more complex and can do many basic tasks as well as any computer. The extra functionality that has transitioned the smartphone from a phone-call-only device to a multipurpose portable device, which makes it more power hungry than ever before.

The internal battery pack is the main source of storing and delivering power to portable-device circuitry. Battery-charger ICs are responsible for charging the battery pack safely and efficiently. They must also control the power delivery to the system to maintain normal operation while plugged in to wall power. The battery pack is required to store a large amount of energy and be charged in a short amount of time without sacrificing weight and volume. The increased charge and discharge currents, as well as the smaller physical size, make the packs vulnerable to physical and thermal stresses. Therefore, battery chargers are no longer required to perform just as a simple standalone charger.

To maintain reasonable charge times and safe charging conditions, a battery-charger IC is required to be flexible because it must guarantee power to the system at all times and provide proper protection for both the battery and system. This article explores single-cell battery-charger solutions and includes a detailed discussion about the performance and constraints of chargers for compact high-power applications.

An overview of single-cell charging solutions

Rechargeable batteries are vital to portable electronic devices such as cell phones and wearable electronics. Charging circuits must be carefully designed and are highly dependent on three factors: battery chemistry, power levels, and system load. Different battery chemistries require different charging methods. An application's power requirements directly impact the charging system's cost and size. Finally, the system power requirement must be considered to determine the necessity of a power-path versus a non-power-path system.

Lithium-Ion (Li-Ion) batteries are becoming the chemistry of choice for many portable applications for several reasons. They offers a high capacity-to-size and weight ratio, and they have low self-discharge characteristics. They also have high cell-voltage characteristics, typically 3.6 V, which allows a battery pack to be designed with only one-cell. Despite all these advantages, Li-Ion batteries are fragile to stress. They require many special considerations regarding charge current, regulation voltage, trickle charge levels, temperature monitoring, and so on.

There are two basic types of charging methods: linear and switch-mode charging. Switch-mode charging minimizes power dissipation over a wide range of AC-adapter voltages, but consumes more board space and adds complexity. Additionally, switch-mode applications generally are higher cost than an equivalent linear application.

Linear chargers are smaller and great for noise-sensitive equipment. However, they are not as efficient across the entire charge cycle as their switch-mode counterparts. When selecting a charging method, the designer makes the decision by prioritizing cost, space, bill-of-material (BOM) count, and efficiency (thermal loading).

The variety of system requirements drive many different battery-charger solutions; from a simple standalone charger to an embedded charger that also provides system power. System requirements include, but are not limited to:

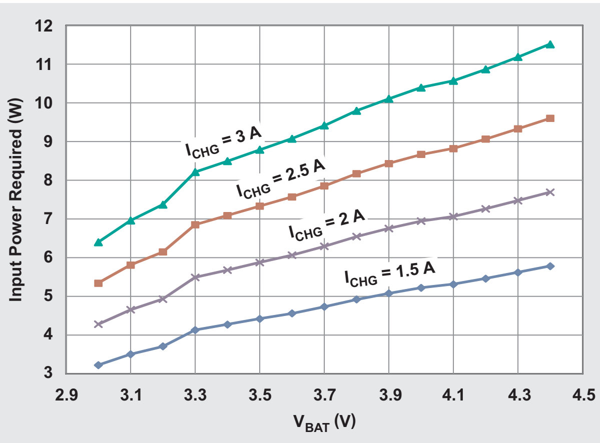
- The need for dynamic power path management (DPPM) that guarantees system instant-on with discharged or disconnected battery.
- Low FET $R_{DS(on)}$ for both the battery and system path to guarantee acceptable overall system efficiency and thermal management.
- High charge current to support high-capacity battery packs and shorten the charge time.
- Input-voltage dynamic power management (DPM) that supports the limitation of any adapter and/or USB port.

Compact single-cell charger applications

Power requirements (adapter limitation)

Currently, most smartphone adapters are specified for 5- to 10-W maximum output power. Figure 1 shows the input power needed from the USB port or adapter for different charging current levels. For a 1.5-A charge current, the required power increases linearly from 3 W to 5 W as the battery voltage increases from 3 V to full charge. For a 3-A charge rate, up to 12 W is needed from the input during the charge cycle. In this scenario, depending on the battery's state of charge, a 5-W or 10-W adapter can crash and the system collapses. To prevent this from happening, the charger is required to have some kind of protection to reduce the power drawn from the input.

Figure 1. Input power needed for different charge currents



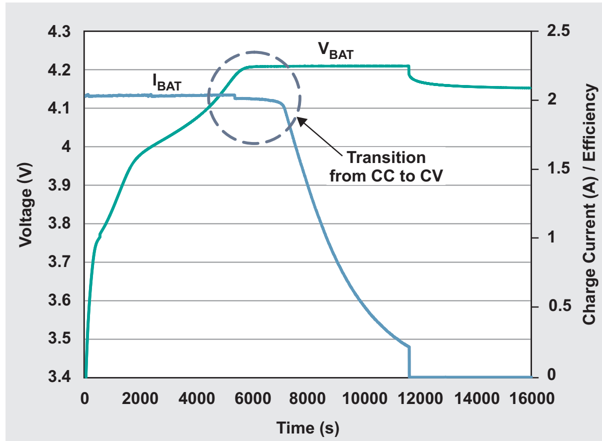
A battery charger such as the bq24250 from Texas Instrument has dynamic power management (DPM) that monitors input voltage (V_{IN_DPM}). During the normal charging process, if the input power source is not able to support the programmed or default charging current, the input voltage decreases. If the input voltage drops to the V_{IN_DPM} threshold set by the designer, the charge current is reduced. This limits the power drawn from the input supply and prevents further drop of the input voltage. This feature ensures IC compatibility with adapters that have different current capabilities without any hardware change.

Charge time

As described earlier, charge time depends on the battery capacity and charge rate. The easiest way to decrease charge time is to charge at a faster rate. However, charging a battery with higher than 80% (0.8C) of the battery's full capacity causes stress on the battery. This decreases its lifetime or possibly damages the pack with catastrophic results. Texas Instruments has developed charge-time optimization of charge cycles to reduce charge time for a given charge rate compared to other solutions.

The charge cycle of Li-Ion batteries is mainly composed of three phases: pre-charger (trickle), fast charge (constant current), and taper (constant voltage). The transition between one phase to another is not ideal for many switch-mode chargers. Figure 2 highlights the phase transition from constant current to constant voltage in a legacy charger circuit. Both voltage and current do not have a sharp transition. This behavior causes both time and power loses during the charge cycle.

Figure 2: Charge cycle of a legacy charger without time-optimizer technology



A Li-Ion battery charger from Texas Instruments improves this transition using the time-optimizer technology. Figure 3 shows a charge cycle of the same battery and under the same charging conditions as in Figure 2. The charge time is reduced by more than 15%. The transition is much sharper on the new charger, which spends more time in the fast-charge (CC) phase before transitioning into the taper (CV) phase. This puts more Coulombs into the pack at a faster rate, thereby reducing the charge time without increasing the charge rate.

Figure 3: Time-optimized charge cycle for a switch-mode Li-Ion battery charger

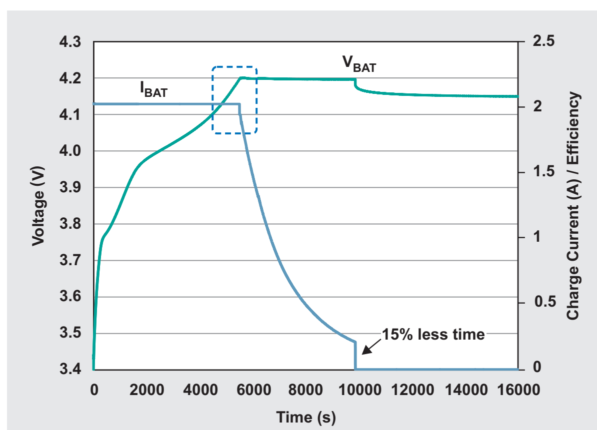
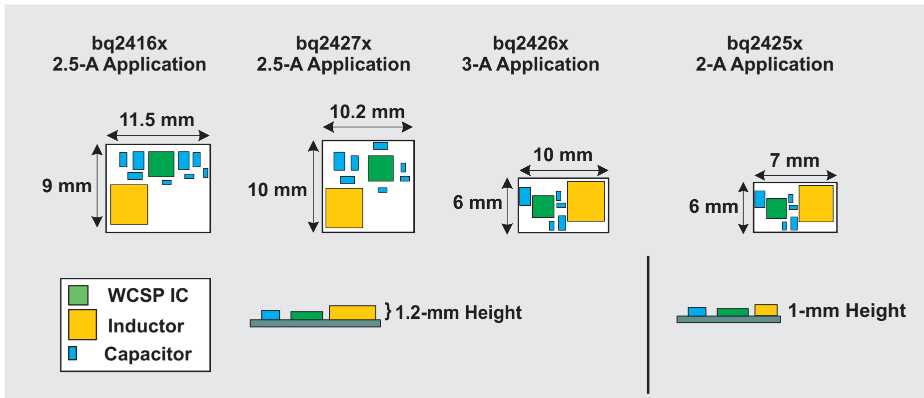


Figure 4: DPPM charger application area for different applications



Board size and BOM cost

For higher charge rates, linear chargers become less attractive. Their reduced efficiency over the charge cycle increases thermal loading on the system. This is especially true in size-constrained boards and high-power applications. These conditions drive the requirement for a fully-integrated switch-mode charger.

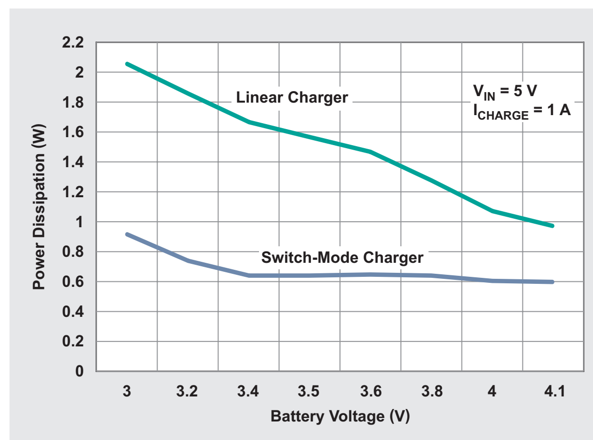
Vendors such as Texas Instrument are pushing the envelope of innovation to meet market demand by reducing the BOM cost and board space without sacrificing device performance. For example, the bq24250 is a highly-integrated single-cell Li-Ion battery charger and system power-path management IC targeted for space-limited, portable applications with high-capacity batteries. Figure 4 shows a range of devices with actual application area size. For instance, the bq2425x family of chargers can provide a charge current of up to 2 A, an economical BOM, and a 42-mm^2 application area.

Thermal performance and efficiency

Reducing the size of the charger area affects the thermal performance of the whole board. Less available area results in less space to dissipate the heat caused by the power dissipated during charging. For a given board area, the only way to reduce thermal loading is to improve charger efficiency during power conversion. Higher efficiency results in lower power dissipation. Thus, less heat is generated from the IC and the board.

When comparing power dissipation between linear and switch-mode chargers in higher power applications, linear chargers becomes less desirable as the power dissipated can be very high—especially for lower battery voltages. This is because the linear chargers use a linear regulator to do the power conversion. On the other hand, switch-mode charging is much more efficient over the entire battery voltage range and results in less power dissipation. Figure 5 shows a comparison in power dissipation between linear and switch-mode chargers.

Figure 5: Comparison of power dissipation between a linear versus switch-mode charger



Choosing a switch-mode charger over a linear charger is a logical choice to improve charger thermal dissipation on the board. Lowering the $R_{DS(on)}$ of the integrated FET inside the switch charger helps improve charger efficiency at high currents. This is because most power dissipation at higher currents for a switch charger is caused by the FET's $R_{DS(on)}$. The bq24250 Li-Ion battery charger has integrated power FETs with low $R_{DS(on)}$. Internal high-side and low-side MOSFETs are rated to only 100 mΩ each.

This helps reduce power dissipation from the input to system output. The $R_{DS(on)}$ of the FET switch to the battery is only 20 mΩ. This also helps reduce losses during battery charging and discharging. Figure 6 provides system efficiency data for the bq24250, which can be as much as 95%.

Battery protection and battery-life extension

A major issue with the high-power portable electronics is battery life cycle. The reduction of battery capacity over time greatly impacts the user's experience by reducing runtime. The main contributor to improve the battery pack life cycle is to reduce stress during charge and discharge. Li-Ion batteries are very sensitive to stresses caused by overcurrent or overvoltage on the pack.

Battery-charger ICs such as the bq24250 can regulate the battery voltage with ±0.5% accuracy in room temperature. For charge current, this IC provides ±0.75% accuracy for up to 2-A charge current over the 0 to 125°C temperature range. This accuracy allows designers to precisely program the voltage and current level according to the application needs. With these accurate charging parameters, batteries can be charged more aggressively without reducing the life cycle. Thus, charge time is reduced while maintaining a safe charging solution.

Figure 7 shows the accuracy of three charge currents over temperatures ranging from 0°C to 125°C . For up to 1.5-A charge currents, accuracy is within 2% of the typical value shown in the datasheet.

System-off mode (SYSOFF)

During presale shipping and storage, the battery needs to be disconnected from the rest of the system to prevent depleting the battery. The bq24250 battery charger has a SYSOFF mode that can be set to turn off the battery FET and disconnect the battery from the system. When the SYSOFF mode is used, the leakage current from the battery into the IC is reduced to less than 1 µA (Figure 8). The designer programs the system to automatically exit SYSOFF mode when the end customer plugs a power supply into the charger.

Application flexibility

In today's highly competitive market, most players are constantly pursuing lower costs, which potentially can bring higher margins and greater competency. Being able to repurpose the same chip for various products or multiple generations has a direct cost savings for different system designs. It also shortens the application learning curve and avoids unnecessary risk by using a known working solution.

The market is pushing for a family of battery chargers that integrates several features to provide flexibility for different applications. One example is a charger with a wide input-voltage range so it is applicable for a broad range of adapters, which could potentially reduce inventory costs. The flexibility in charge currents can support the higher current for applications like power banks and smartphones as well as low-level charging to applications like *Bluetooth*® headsets.

Figure 6: System efficiency of the bq24250 Li-Ion battery charger—4.2-V regulation

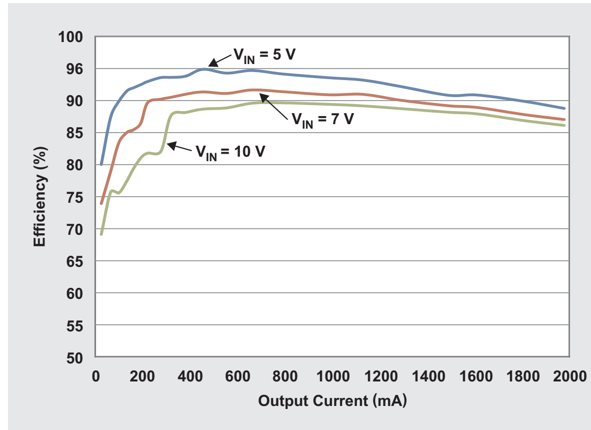


Figure 7: Charge current accuracy versus temperature

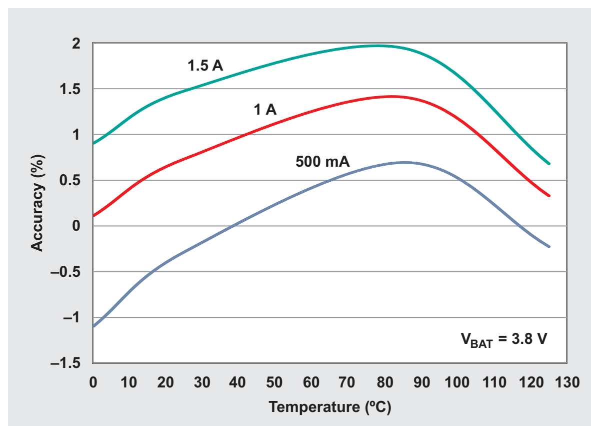
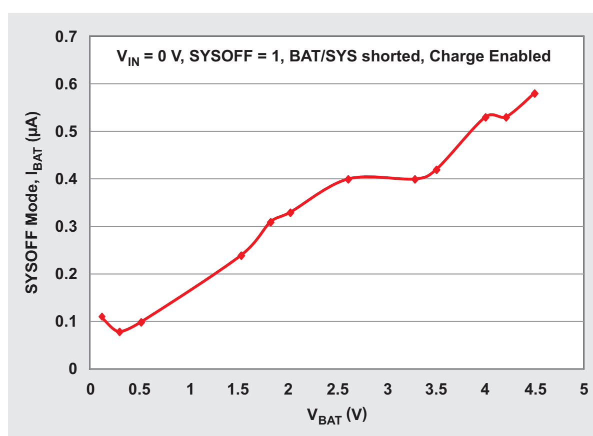


Figure 8: Battery leakage current in SYSOFF mode



Many chargers provide two chip-control schemes: I^2C communication and standalone. This allows the tailoring each application as needed. In I^2C mode, designers can program various parameters such as V_{IN_DPM} threshold, charge current, input current limit, regulation voltage, and termination level. When operating in standalone mode, where the host control is not desired, designers can use external settings to program the above parameters and utilize external pins to select different levels of input-current limit and to enable/disable the chip.

The BC1.2-compliant, D+/D– USB detection feature offers greater flexibility for more robust USB charging. In the past, USB charging was very straight forward where the device took power directly from the USB port to the battery with little control. In today's high-power applications, devices are requesting far more power from the USB port, which leads to more complicated standards and protocols being implemented. Furthermore, with the various USB standards normalized in the same USB port connector, the ability to recognize which type of device is connected is a very useful and competitive feature.

Conclusion

There are many options available for charging high-power portable devices. Currently available charging ICs that support power-path management and high charging current with improved efficiency can reduce charge time, thermal stress and solution size. A low-cost BOM and a small size solution bring the device cost down without sacrificing size and capability.

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Industrial-strength design considerations to prevent thermal and EMI damage

By Rick Zarr
Technologist, High-Speed Signal and Data Path

Introduction

Electronic controls and sensing in industrial applications enables or greatly improves many aspects of manufacturing, machining and production. However, electronics must survive within the harsh environments used to produce materials such as steel, petroleum products and chemicals, or in mines where the environment is extremely hot, dirty and humid. Careful considerations must be taken when designing any system that must endure these conditions that can include extremely strong electric and magnetic fields. Keeping these conditions in mind and designing for worst-case conditions will ensure that these systems continue to operate, regardless of the environment where they are installed. This article examines some of the key design obstacles and includes worst-case design techniques to achieve survivable solutions for industrial applications.

The Importance of Reliability

In our modern world of disposable phones and low-cost consumer electronics, why should engineers worry about periodic field failures on a factory floor? In reality, it is not the cost of the electronics and possibly not even the cost of maintaining the system. Rather, it very well could be safety or the loss of plant productivity that could dwarf the cost of the latter. Large-scale manufacturing plants can cost billions of dollars to build and millions more to run. A single shutdown event due to some system failure could take days to restart, costing potentially hundreds of thousands, if not millions of dollars, in lost revenue per day while off-line. Also, whenever human life is at stake, a failure that causes injury is unthinkable. In other words, failure in these facilities is not an option.

Electronic controls are often installed into areas that are inaccessible to humans during normal operation, such as near a furnace or behind a large piece of equipment. This means that to reach the control system, the production area must be shut down for access. Industrial systems are installed with the intention that they will operate for many years (sometimes for the lifetime of the facility) without ever failing or requiring maintenance. This is the true challenge for designers of industrial systems.

The challenge of thermal management

Heat is a byproduct of electronics due to the operation of transistors and other components. It must be well managed or rising temperatures will degrade or damage devices. To understand why, simply reviewing how semiconductors are fabricated illustrates the problem.

Integrated-circuit (IC) fabrication uses thermal processes such as diffusion and annealing to move material around and within structures. The atoms of the material migrates or forms crystal structures during these processes, which occur at fairly elevated temperatures (1200ºC or greater). However, unless the IC is held at absolute zero (0º K or –273.15ºC), thermal motion will continue the process of diffusion, although much slower than during fabrication.

A curiosity of silicon used to fabricate ICs is that it has a non-linear relationship to resistance and temperature. At room temperature, silicon shows an increase in resistance as the IC's operating temperature increases. However, as the temperature increases (above recommended limits), the resistance begins to decrease, resulting in a potential positive-feedback condition. This also can occur for various other systemic reasons inside an IC that may result in a thermal runaway condition. As more current flows, the resistance of the path decreases due to thermal heating, ultimately destroying the IC by thermal damage.

Many power ICs and voltage regulators employ thermal shutdown of the output stages to prevent this runaway condition from permanently destroying the IC. However, this is still a fault condition whereby the system will fail to continue operation. Even if an IC never reaches thermal shutdown, long term reliability suffers from elevated temperatures that can result in premature failure. ICs must be used in accordance with the datasheet's recommended operating conditions so that the temperature of the IC die inside the package is kept at a safe value.

To manage the operating temperatures in equipment, manufacturers often use fans to increase the airflow over heat-generating components. Unfortunately, fans are notoriously unreliable over long periods. Plus, industrial equipment is often sealed off from the environment, which prevents cooling with outside air. Heat must be carried away via a thermal path from the ICs to a point of lower temperature.

Starting with the die as a point of heat source, the thermal impedance specified in the IC datasheet must be used to calculate the thermal rise based on the rate the heat flows away from the device. The thermal impedance is given in degrees centigrade per watt of power dissipation of the IC along with the path the heat will travel. For instance, from the junction (die) to the IC's case is referred to as *Theta Junction to Case*, or θ_{JC} (pronounced theta sub JC).

These values are extremely important. For example, a small linear regulator such as an LM340 in a SOT-223 package has a θ_{JA} (thermal impedance from the junction to the ambient air) of roughly 50ºC/W with an unlimited copper plane as the heat-sink. If the input voltage is 5 V, and the output voltage is 1.8 V (a common CMOS core voltage), with a 1-A load, the power dissipation of the regulator will be 3.2 W. This means that even with a large surface area on the PCB utilized as a heat-sink and the ambient air temperature is 20°C, the die's temperature still rises to 160°C. This greatly exceeds the device's normal operating temperature and could result either in a thermal shutdown or damage over time.

In this example, nothing could be done to make the heat flow away from the die unless a lower thermal impedance (other than copper) is tied directly to the case. The heat simply cannot flow away through the PCB copper fast enough to prevent the temperature from rising within the IC at that level of power. A solution here would be to use a more efficient method to convert the 5 V to 1.8 V (such as an LMZ10501 nano-module switching regulator). Another option is to use a package with much lower thermal impedance, which incidentally occupies more PCB surface area .

Thermal impedances, like their electrical cousin, can be summed in series to calculate the temperature rise. For example, $T_{Rise} = P_{Dissipated} \times (\theta_{JC} + \theta_{CA} + \theta_{AE})$ where the thermal impedances are θ_{JC} (junction to case), θ_{CA} (case to ambient) and θ_{AE} (ambient to environment or to the environment where the equipment resides). Selecting packages with very-low thermal impedances help transfer heat from the device. Also, adding aluminum heat sinks or heat pipes to the case can help provide a lower thermal-impedance path to the air. This reduces the operating temperature, which greatly improves long-term reliability.

Electromagnetic considerations

Managing thermal issues with equipment enclosed in an air-tight box is not the only problem. Now consider the equipment's electromagnetic (EM) environment and electromagnetic interference (EMI). Many engineers consider EMI susceptibility as damage caused by lighting or other voltage overstress condition—and they would be correct. However, that's not the only failure-inducing mechanism of extreme EM fields. More on this later.

Electrostatic damage mitigation is a reality that designers must address. If cables (including power) come into the chassis, then there is a path for large voltages to be present in that equipment, regardless of normal operating conditions. Power supplies often are protected intrinsically by design from large voltage spikes. The input stages might even have high-speed voltage monitors that clamp the input to prevent overvoltage related damage. However, when equipment is connected via wired networks, these connections provide a path with a means to store charge through the wire capacitance. It is not uncommon to find a thousand feet of wire between a sensor module (with active electronics) and a controller.

There are phenomena in nature that can destroy equipment, such as a direct lightning strike. However, there is another more-subtle effect known as cross striking. This phenomenon occurs when a highly-charged thunderhead slowly drifts over the network with long cabling and induces opposite charges on the wire (Figure 1). Normally, the charge is held in position by the charge high above in the cloud. However, if another cloud with an opposite charge drifts nearby, this can cause an electrostatic discharge (lightning) high above the network between the two clouds.

Figure 1. Conditions for cross-striking when oppositely-charged clouds float by

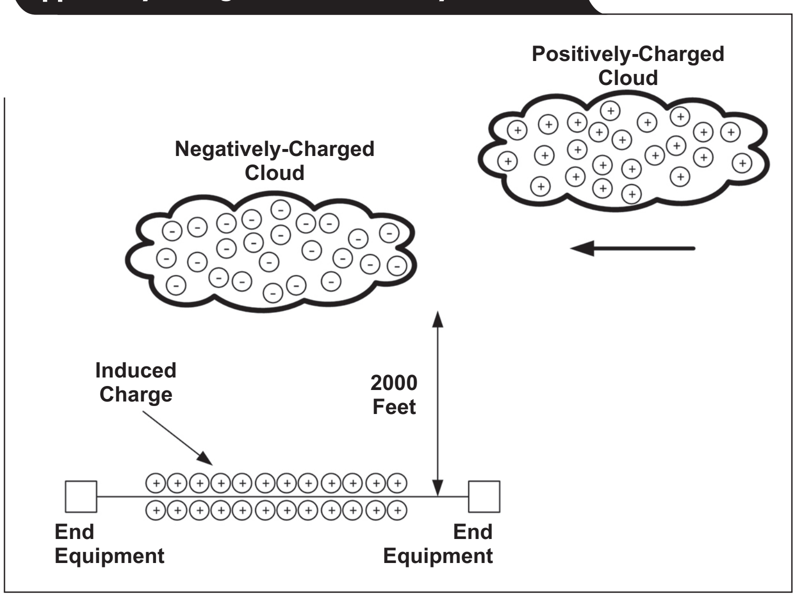
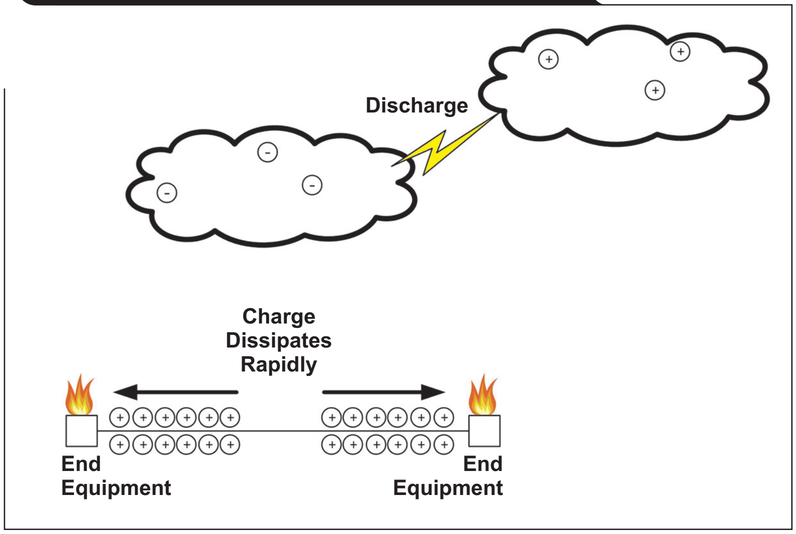


Figure 2. A cross-strike event may result in damage to end equipment



Once the charge in the cloud directly above has dissipated, the induced charge on the wire must also dissipate. As the charge rapidly drains from the wire, extremely large voltages appear at both ends of the cable. If left unchecked, the voltage potentially can destroy whatever is located on either end of the wire (Figure 2). To mitigate this type of damage, arc tubes or spark gaps along with electrostatic discharge (ESD) protection diodes are located in the end-equipment cable termination, providing the charge a path to ground. Otherwise, the path will be through cable drivers or transceivers, which most likely will not survive.

As mentioned earlier, the other type of EMI doesn't directly destroy ICs. Instead, it causes them to shift their operating points; or cause drift from specified limits. Many manufacturing facilities now use microwave heaters or other RF sources in the process. These large RF fields can induce currents into various parasitic diodes and active components found within an IC. If the IC was not designed to handle these fields, internal bias points may shift, changing the circuit's operating point.

A common nonindustrial EMI problem can be observed in many speaker phones. Amplifiers are often susceptible to RF sources such as cell phones. If the speaker phone is in use, often times a buzzing can be heard on a call while holding the cell phone close. The RF energy from the cellular transmitter is parasitically demodulated inside the amplifier chain and is heard audibly through the speaker.

However, in an industrial-control application, this phenomenon can be far more serious. It often manifests itself as an offset in precision measurements. That could mean a temperature-sensing error of several degrees or other measurement errors with remote sensors. Many processes must be held to extremely tight tolerances. Any deviation may result in either a catastrophic failure of the production process, or at a minimum substandard quality.

To address the problem, designers need to use RF-hardened components (not to be confused with radiation-hardened ICs). ICs such as the LMP2021 (single) and LMP2022 (dual) operational amplifiers are designed specifically for precision performance in the presence of high-level RF fields. Using ICs like these will mitigate errors in precision applications caused by the presence of RF interference.

Conclusion

The industrial environment is harsh and unforgiving to electronic systems. Designers must take into account the conditions of elevated temperatures as well as other sources of damage and interference. Much of the heavy lifting is now done by the ICs themselves because they are designed to handle extreme conditions. Ultimately, however, it is the designer's decisions that will result in a system that operates continuously for years without failure.

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