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Power Management Fundamentals

Qorvo Special Edition

by David Schnaufer,
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and Michael Day

for dummies
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Introduction

Power efficiency, voltage conversion, and power delivery to subcomponents are critical elements in the design of all consumer electronic devices. The applications range from 5G base stations, data centers, and automobiles to the Internet of Things (IoT). Power management is also essential in the design of personal household electronics and connected devices.

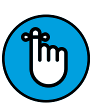
Today's highly integrated, configurable power supply solutions implement a built-in intelligence that greatly simplifies the design process by eliminating the need for external components. Doing so reduces bill-of-materials costs, improves system efficiency, and incorporates system control and system flexibility into a single integrated circuit (IC).

Foolish Assumptions

This book is written for both technical and nontechnical readers. If you're an executive, salesperson, or design engineer, this book is for you. All you need is a general curiosity about power management integrated circuits (PMICs).

Icons Used in This Book

Throughout this book, we occasionally use icons to call attention to important information. You won't see the typical cute grinning faces or other flashing emoticons, but you'll definitely want to stop and pay attention! Here's what you can expect:



REMEMBER

The Remember icon points out information that you'll want to put in storage, your memory, or whatever you use to keep track of important information like birthdays and phone numbers for later use.

TECHNICAL STUFF

Anything marked with the Technical Stuff icon is targeted toward your inner geek. Who knows? You may come away with some useful knowledge to increase your nerd status.

Beyond the Book

Although this book is full of good information, we could only cover so much in 24 pages! So, if you find yourself wanting more after reading this book, just go to `www.qorvo.com/products/power-management`, where you can get more information about Qorvo's PMIC technologies and products.

Where to Go from Here

Whether you're new to power management integrated circuits or a seasoned engineer looking to use the latest technology in your designs, you'll find this book useful.

Each chapter in this book stands on its own, so you can skip around if you like. If you're familiar with the topics in a chapter, you can skip it. We provide cross-references to information in other chapters of the book, so you can always find what you're looking for.

IN THIS CHAPTER

» Brushing up on the fundamentals of power supply

» Looking at DC-DC voltage regulators

» Introducing PMICs

Chapter 1 Understanding Power Management

In this chapter, you learn the basics of power management, including the types of circuit design required for different applications. You also find out what a power management integrated circuits (PMIC) is and how today's versatile PMICs can take the place of several types of voltage regulators.

Grasping Power Supply Fundamentals

The type of DC power management subsystem a device or other electronic system requires depends on its power source. Possible power sources include AC, battery, DC, and ultra-low-power DC (energy harvesting).

Most battery-powered electronics use lithium-ion (Li-ion) or lithium polymer (LiPo) batteries. A battery pack may contain several batteries, combined either in series or in parallel. Figure 1-1 shows some examples.

Here are the voltage and current capabilities for each of these configurations:

» **Batteries arranged in series** increase battery pack voltage while also increasing the entire battery package capacity.

- **Batteries arranged in parallel** do not increase battery pack voltage, but they do increase the overall battery pack current capability and capacity.
- **Batteries configured both in series and in parallel** increase voltage, current capability, and capacity simultaneously.

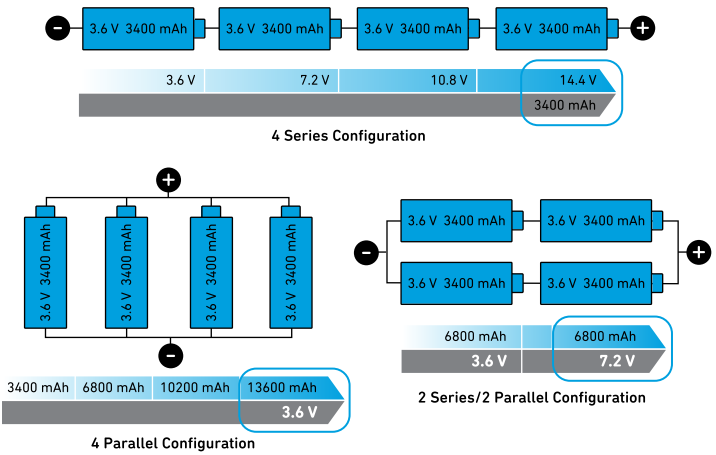


FIGURE 1-1: Series and parallel battery configurations.

In some battery-powered applications, the system components may not be able to directly use the battery's power. The components may require a lower or higher voltage to function properly. The battery voltage also changes as the battery is charged and discharged. DC-DC converters are used to monitor and stabilize this unregulated battery input voltage. These converters are often referred to as *voltage regulators* because they step up, step down, or regulate the voltage as required (see Figure 1-2) and supply it to system subcomponents.

DC-DC regulators may be isolated or non-isolated, depending on whether the input ground is connected to the output ground:

- **Isolated converters** provide isolation between the input and output voltage, usually using a transformer or capacitive power transfer.
- **Non-isolated converters** have a DC path from input to output ground and share the input and output ground connections.

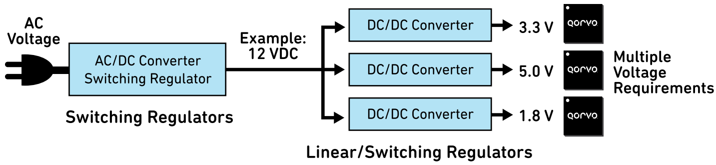


FIGURE 1-2: Switching and linear regulators.

Categorizing DC-DC Voltage Regulators

DC voltage regulators fall into one of two categories — linear or switching — depending on the voltage conversion method they use. These are the two basic types of regulators used in electronic devices such as cameras, phones, wearables, and computers. Based on the input voltage, the output voltage, and the desired current load, design engineers select the appropriate DC voltage regulator for their system design.

Linear regulators

Linear regulators convert a voltage input (V_{IN}) to a different voltage output (V_{OUT}) using a *linear* component (that is, a resistive component) to regulate V_{OUT}. Linear regulators typically:

- Dissipate power.
- Are used for lower current and lower power supply rails.
- Are not highly efficient.
- Are used for low-noise power supplies.
- Are suitable for sensitive analog ICs such as sensors, phase locked loops, and so on due to their low ripple and noise.

TECHNICAL STUFF

A key type of linear regulator is the *low dropout* (LDO) *linear regulator.* An LDO can maintain a regulated V_{OUT} with a V_{IN}, that is close to V_{OUT}.

Switching regulators

Switching regulators convert V_{IN} to a different V_{OUT} via a *switching* element and use external inductors and capacitors to smooth the output voltage V_{OUT}. Switching regulators are typically more efficient and can support higher current outputs than linear regulators. The output is regulated but still has ripple or switching noise that remains after the filtering occurs.

REMEMBER

Switching regulators can be classified according to the relationship between the input and output voltage:

- **Buck switching regulator:** V_{OUT} is less than V_{IN}.
- **Boost switching regulator:** V_{OUT} is greater than V_{IN}.
- **Buck-boost switching regulator:** V_{OUT} is variable and could be lower than, higher than, or equal to V_{IN}.

These four types of regulator topologies — LDOs and three switching regulators (buck, boost, and buck-boost) — are commonly used by design engineers. In the following sections, we look at all of these in more detail.

LDO regulators

A low-drop linear regulator is a DC linear voltage regulator that can regulate the output voltage even when the supply voltage is very close to the output voltage. For LDOs, the dropout voltage should be as low as possible to minimize power dissipation and maximize system efficiency (see Figure 1-3).

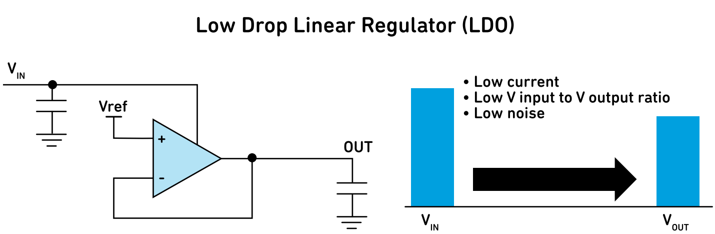


FIGURE 1-3: Low drop linear regulator (LDO) circuit and response.

Compared with switching regulators, LDOs usually have a higher power supply rejection ratio (PSRR), which means they generate a low-noise output voltage. They're typically devoid of any ripple, making them useful for reducing noise or ripple from their input power supply.

LDOs have low standby current consumption, which makes them good solutions for portable and wireless applications.

Buck converter

To *buck* in this context means to reduce or step down. A buck converter is a step-down regulator that efficiently produces a V_{OUT} that's less than its V_{IN}. The buck circuitry consists of an inductor, switching FETs or diode, capacitor, and error amplifier with switch control circuitry (see Figure 1-4). It operates by varying the amount of time that the metal-oxide semiconductor field-effect transistor (MOSFET) is on and applies power to the inductor. The buck converter's high efficiency comes from the fact that its MOSFET is either fully turned on or fully turned off. It does not operate in a state that is between on and off (resistive) like in a linear regulator.

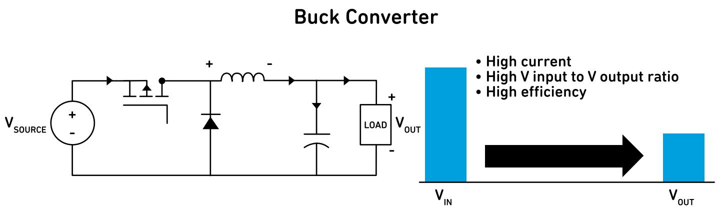


FIGURE 1-4: Buck converter circuit and response.

A buck converter generates a switching waveform that is either pulse width modulated (PWM) mode or pulse frequency modulated (PFM) mode, and filters it using external inductor and capacitor filter components to create a smooth output voltage V_{OUT}. This efficient voltage conversion method extends battery life, reduces system heat, and allows for small product sizes.

Buck converters are used in many applications that deliver power via USB connections and other computer peripherals. They're also used in smartphones, tablets, portable devices, and many other electronic devices.

Boost converter

To *boost* in this context means to step up. A boost converter steps up the V_{OUT} from its V_{IN}. Boost converters come in handy when you want to boost an input DC voltage of 3.3V up to a V_{OUT} of 5.0V, for example. Such a boost is common in many Li-ion or LiPo battery applications.

The boost circuitry consists of the same components as a buck (an inductor, switching field-effect transistor [FET], or diode, capacitor, and error amplifier with switch control circuitry), but are connected differently. It also operates by varying the amount of time that the MOSFET is on and applies power to the inductor. (see Figure 1-5).

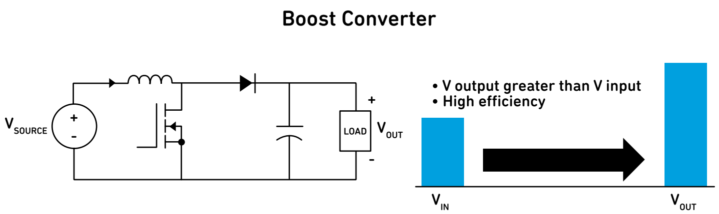


FIGURE 1-5: Boost converter circuit and response.

Buck-boost converter

A buck-boost converter is a switch mode converter that combines the buck and boost principles into a single regulator. It handles a wide range of input and output voltages. The control circuitry adjusts the MOSFET on and off times to either buck down or boost up the input voltage as needed to get the required V_{OUT} (see Figure 1-6).

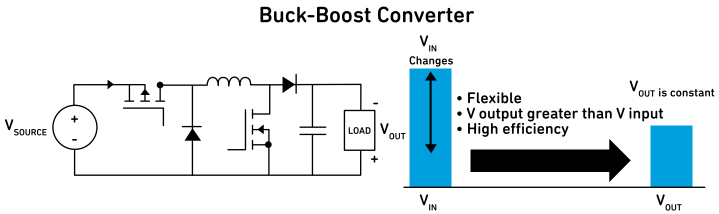


FIGURE 1-6: Buck-boost converter circuit and response.

In addition to the standard buck-boost shown in Figure 1-6, there are several other types of buck-boost converters like the Sepic, Cuk, and Zeta converters. They all can regulate the V_{OUT} lower than, higher than, or equal to V_{IN}.

Introducing Power Management Integrated Circuits

PMICs are integrated circuits used for voltage conversion, voltage regulation, and battery management. They handle power system sequencing, supply power to multiple loads, and protect against unsupported overvoltage and undervoltage conditions, overcurrents, and thermal faults.

A single PMIC can manage multiple external power sources, mapping the different system requirements to appropriate regulator output voltages. You can also use them with different processors, system controllers, and end applications by simply altering register settings or firmware, rather than fully designing a new integrated circuit (IC).

The PMIC market is rapidly growing due to several trends. One is consumers' desire for wireless mobility, which is driving demand for smaller, battery-powered devices that need more highly integrated power management solutions, as shown in Figure 1-7. This figure shows how the Qorvo PMIC solution significantly reduces both component count and overall solution size.

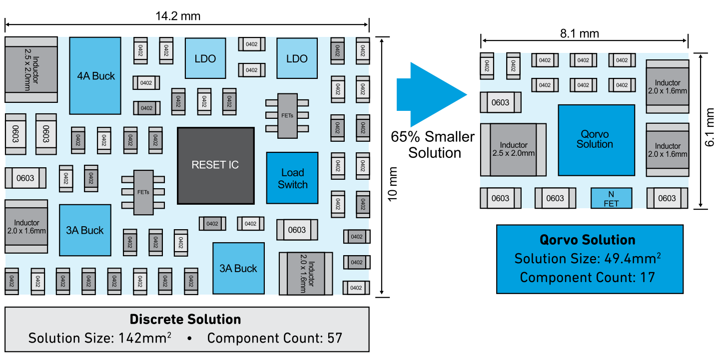


FIGURE 1-7: Discrete power management systems are migrating to one integrated PMIC solution.

There is also growing consumer and business demand for products that save energy, minimize environmental impact, and reduce carbon emissions. This global "green" trend has increased the demand for power-efficient electronic products, making power management an important and sought-after feature.

The All-in-One PMIC

One key reason that today's PMICs are so versatile is that they can serve several or even all of an application's voltage regulation functions (Figure 1-8). These versatile PMICs can be manipulated via firmware to function in many different applications, eliminating the need for costly hardware circuitry changes. This allows for a smooth transition between applications and reduces the time-to-market for products.

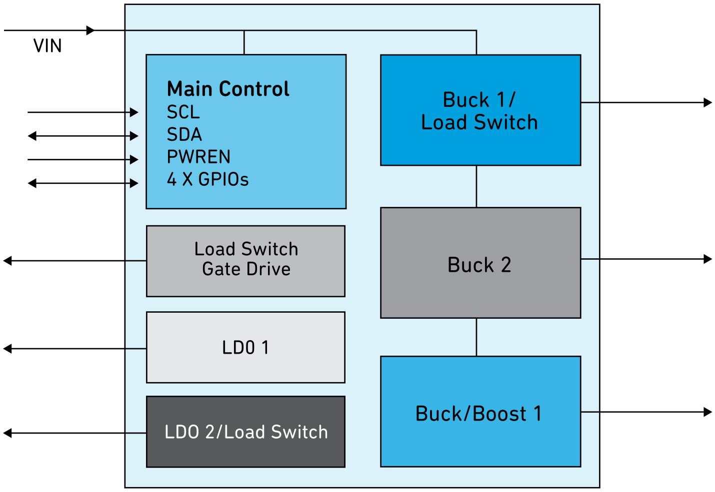


FIGURE 1-8: Example of a high-level block diagram of a PMIC.

IN THIS CHAPTER

- » Looking at linear and switching regulators
- » Handling noise and ripple
- » Managing EMI in switching regulators
- » Focusing on thermal management and efficiency

Chapter 2
Power Management Types

Today's PMICs can perform a wide variety of functions in electronic systems, such as the following:

- » DC-to-DC conversion and/or regulation
- » Supplying several power rails
- » Battery charging and management
- » Selectively managing power delivered to system components to optimize power usage
- » Regulating power to the system to manage power dissipation or battery life
- » Power source selection
- » Power rail sequencing
- » Power rail ramp-up or ramp-down timing
- » Limiting current and protecting components against overvoltage or overcurrent faults
- » Alerting the system controller of power failures
- » Providing backup power

The power management function is becoming increasingly integrated with other hardware components in the design to maintain efficiency and simplify overall system level control.

This chapter looks at some of the key considerations when selecting and designing a power management system for specific applications.

Comparing Linear and Switching Regulators

As we explain in Chapter 1, there are two basic types of voltage regulators: linear and switching. Each type has pros and cons.

REMEMBER

Linear regulators provide a quiet output and are great for lower power output applications. However, they're not very efficient and can only be used to step down V_{OUT}. Switching regulators are efficient, flexible, and small, but they emit high-frequency noise.

Linear regulators have been around for quite some time. They initially operated in the 5 volt logic voltage range but now also support higher voltages in the 1 to 24 volt range. Their current capacity has also increased from the low milliamp ranges to many amps.

Switching regulators use a switching FET to transform the DC (nearly constant) input voltage into an AC waveform (switching between two values), which is then converted back to DC at a different output voltage using capacitors and inductors. In this way, although these switching regulators gain the advantage of efficiency and size, they introduce noise and ripple.

Dealing with Noise and Ripple

All switching power supplies, regulators, and controllers emit some ripple and noise on the output. The ripple and noise show up as an AC waveform overlaid on the DC output voltage. The ripple and noise are a product of the system's switching topology, switching frequency, and its external filtering components.

REMEMBER

A switching power supply's ripple waveform represents the charging and discharging of the output filter capacitance at the switching frequency. The input voltage is switched on and off through the power stage to control and regulate the $V_{OUT.}$ Output filtering is used to reduce the AC ripple created by the on/off switching action from the pulse width modulated (PWM) or pulse frequency modulated (PFM) signal. Filtering the output waveform significantly reduces the ripple, but it can never completely remove the AC ripple.

Managing EMI in Switching Regulators

TECHNICAL STUFF

In switching regulators, a DC voltage is converted to a chopped or a pulsed waveform. This pulsed waveform is inherently "noisy" and in some cases can result in *electromagnetic interference* (EMI). The frequency of the EMI occurs at the fundamental and harmonics of the power supply's switching frequency and pulsed waveform's rise and fall times.

All semiconductors and capacitors have some parasitic inductance associated with their construction. Traces on a PCB layout also have parasitic inductance. EMI that could potentially interfere with communication signals or sensitive analog functions can be generated when the harmonic frequencies in the pulsed waveform interact with these parasitic inductances.

Power supply designs must make tradeoffs between EMI, size, and efficiency. With any given design, only two of these tradeoffs can be optimized at a time. The lower-frequency noise can be reduced by switching faster and adding additional filtering components at the expense of size and cost. Higher-frequency noise can be reduced by adjusting the pulsed waveform rise and fall times at the expense of efficiency.

PMICs inherently reduce noise because their power components are integrated, which results in smaller layouts and smaller parasitic inductance. They can also optimize the pulsed waveform rise and fall times, switching frequency and duty cycle to generate various output voltages and minimize EMI while maximizing efficiency.

Considering Efficiency and Thermal Management

Efficiency is one of the most important characteristics in semiconductor device design. *Efficiency* is the ratio of the output-to-input power, measured at a given load current with known input and output voltage conditions. A lower efficiency results in larger power dissipation and hotter operating temperatures.

Efficiency is directly correlated with the heat dissipation of the system, its individual components, and the product size. As the temperature rises, performance and efficiency are compromised. The thermal characteristics of an application or device also determine the reliability of components and of the overall product. More heat means reduced product lifetime and lower reliability. Designers must minimize thermal heat, because it can result in a thermal runaway that causes system or component damage.

REMEMBER

Several factors affect the efficiency and thermal operation of a DC power supply, including the following:

- **Conduction losses:** Typical resistive losses in regulator and system components.
- **Switching losses:** Losses due to capacitive charge and discharge or from voltage and current transitions in the regulator's power metal-oxide semiconductor field-effect transistors (MOSFETs) or diodes.
- **Over current:** The condition of the output load current being greater than specified or desired and the power supply being overloaded.
- **Over temperature:** The condition of the overall operating temperature of the system or power supply being higher than the desired or the maximum rating. Components become more resistive at higher temperatures and losses increase.
- **Over voltage:** The condition of the output voltage being above the specified DC voltage and excess power being dissipated in the system wastefully.

IN THIS CHAPTER

- » Considering automotive applications
- » Trying on wearables
- » Examining enterprise and computing applications
- » Looking at portables
- » Considering power loss protection

Chapter 3 Power Management Use Cases

Power management stretches across many markets and industry sectors. *Power management integrated circuits* (PMICs) are implemented into many types of product and perform a range of different functions, including intelligent motor control, power protection circuitry, and DC-DC converter/regulator applications, to name just a few.

With their small size, high efficiency, and low power consumption, PMICs are used in many small devices such as wearables, "hearables" such as earbuds, mobile devices, sensors, and Internet of Things (IoT) devices. These tiny, high-performance PMICs maximize system efficiency and performance while providing design flexibility and lowering the bill-of-materials cost.

REMEMBER

Today's PMICs are very flexible. They can function in many different applications by simply changing register settings or firmware. This capability increases their versatility and decreases manufacturer time-to-market.

In this chapter, we review some growing markets and look at how power management solutions are applied to typical use cases.

Looking at Automotive Applications

The automotive power management semiconductor market is growing exponentially as new, innovative electronic devices migrate into vehicles. These devices are radically changing many aspects of cars and other vehicles, including the driving experience. Applications like connectivity, telematics, motor controls, and safety features are growing in number, and they all require power management for efficient and reliable operation.

The growing popularity of hybrid-electric and all-electric vehicles is further energizing the power semiconductor market. In hybrid-electric and all-electric vehicles, there are many different supply voltages, with varying output voltages, output currents, efficiency levels, and thermal ratings.

The many applications shown in Figure 3-1 for electric or hybrid-electric automobiles require different levels of voltage regulation. Most of the loads in these applications utilize 12V or 24V supply voltages, but some traction motor applications need higher voltages. All these applications require efficient buck, boost, or buck-boost converters to make the many different regulated voltages available throughout the vehicle.

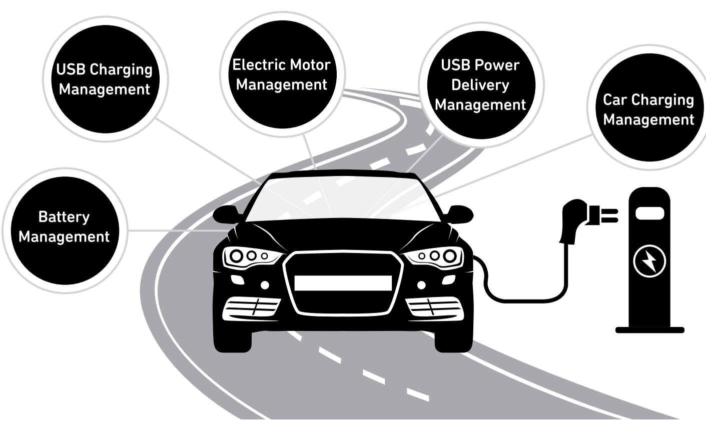


FIGURE 3-1: Automobile power management applications of PMICs.

Trying On Wearables

Today's wearable devices require highly integrated advanced power management. They must provide long battery runtime using small, low-voltage batteries. Only by efficiently managing the system load can the device extend the time between battery charges. High efficiency and low standby currents are critical. The power management subsystem must also handle battery recharging, including wireless charging in some devices.

REMEMBER

A single configurable PMIC can serve several applications within the same device, as shown in Figure 3-2. Many wearable devices have embedded processors, displays, touch screens, sensors, sound or haptic feedback, health monitors, GPS systems, microphone, Bluetooth, Wi-Fi and cellular wireless capability for transmitting and receiving data. All these functions pose a significant drain on the small battery.

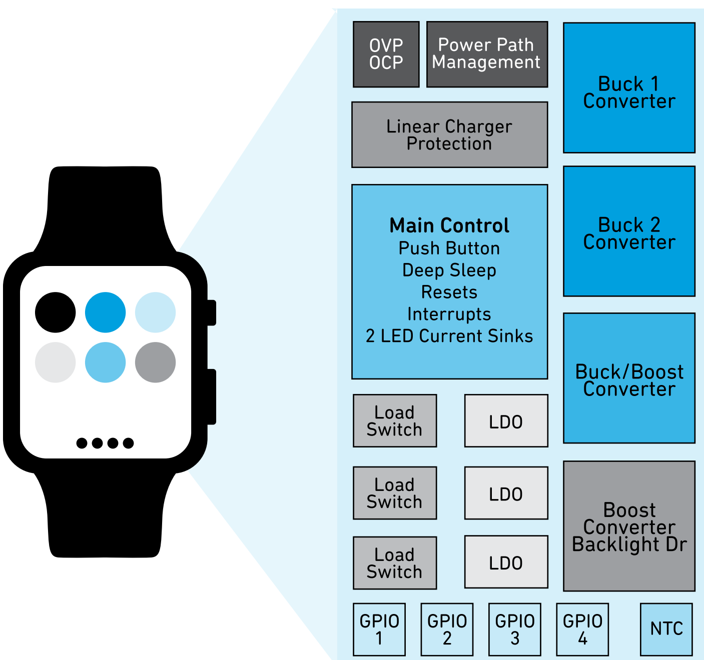


FIGURE 3-2: PMIC for wearables.

To conserve battery life, the PMIC manages all the voltage functions. For example, it may initiate sleep mode when a certain application is not being used and manage the components that must remain on to support the other applications. PMICs play an integral part in managing device low-power states, turn-on states, turn-off states, and standby modes.

Most wearable devices have severe size constraints. To minimize the size of the PMIC, high-density device pin arrangements and advanced packaging are essential. In addition, using high operating frequencies for switching regulators can reduce the external filtering required for switching regulators. Using PMICs minimizes the number of external components and further reduces solution size.

Exploring Enterprise and Computing Applications

A vast and increasing amount of data is collected, stored, processed, and transmitted on enterprise and consumer devices. All these activities consume power, and benefit from efficient power management.

Server equipment, cloud storage, network-based storage, and desktop computers form the bulk of the computing and storage equipment market. This market has specific requirements, including the following:

- High-current regulators up to tens of amps for high-power processors
- Multi-phase regulators to support high-output currents and increase system efficiency
- Small form factor inductors for high efficiency
- Improved dynamic transient response where high current load demands and spikes are seen
- High switching frequency
- High-voltage applications such as 12V, 24V, or 48V input power sources

Fast dynamic responses, tight and accurate output voltage regulation, high-output power and current, and high efficiency are key requirements for products in the enterprise and computing markets.

Picking Up Portables

Portable products such as laptops, tablets, and portable speakers have complex power management requirements. All use switching regulators, which are more efficient and smaller than linear regulators.

In addition, these applications require simultaneous battery charging and system power, which means they must have independent power paths for powering the system and charging the battery. To achieve this, the power management module is composed of a switching charger to power the entire system while also managing battery charge independently and a battery switch to manage charging. The PMIC can manage all these functions.

Surveying Power Loss Protection

Many products in the computing and storage market have built-in power loss protection capabilities. These devices provide backup storage power in the event of an input power failure.

Without power loss protection, power loss could result in data loss or corruption. For example, a write operation might be interrupted before the data is safely stored.

A PMIC power loss protection (PLP) device can store power and then supply this power to the output when input power is lost. The integrated buck converter regulates the storage voltage to a fixed output so the system can continue operating correctly. Capacitors store energy during normal operation and deliver it to the system when a power loss occurs. This energy storage process is called *supplement mode,* because the PLP device supplements the power to the system to allow it time to back up critical data and shut down in a controlled way, as shown in Figure 3-3. This type of shutdown lessens the risk of incomplete actions, data loss, and corruption.

The PLP technology embedded in solid-state drives (SSDs) significantly reduces the possibility of losing data during a power loss event. It continuously prepares for unexpected power loss, thereby protecting the data from corruption and destruction. SSDs with PLP technology contain energy-storing capacitors. The storage capacitors act as a backup power source for the drive, providing enough energy to ensure that any data in temporary buffers can be saved to the SSD memory before power goes away.

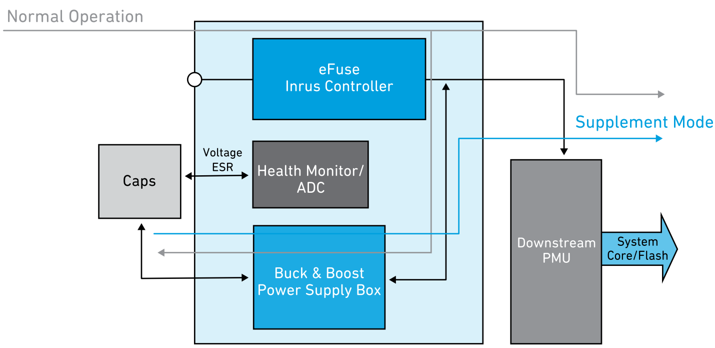


FIGURE 3-3: PLP embedded circuitry.

TECHNICAL STUFF

Integrated boost circuits charge the storage capacitors to high voltage to minimize storage capacitor size. The higher the voltage, the higher the stored energy (since the stored energy is determined by the formula $E = 0.5CV^2$, where C is capacitance and V is voltage). The integrated buck converter regulates the storage voltage back down to a value that the system can use and operate correctly.

A typical PLP PMIC has an integrated autonomous health monitoring circuit that frequently checks the storage capacitor conditions to ensure safe operation. It also provides information that enables the host to estimate the capacitors' remaining life. Some PLP PMICs also implement a multi-channel A-to-D converter (ADC) to help monitor the power system parameters such as input power, storage capacitor voltage, and die temperature.

In addition to their use in SSDs, these PLP PMICs are used in backup power, computing, hot-plug devices, networking storage, and other applications where it is critical to detect an imminent power loss and write data to permanent storage before power is lost entirely.

IN THIS CHAPTER

» Summarizing the key operational benefits of PMICs

» Understanding how PMICs save money

Chapter 4

Ten Key Advantages of PMICs

Power management integrated circuits (PMICs) provide many benefits to the devices in which they are incorporated. Here are the most important advantages you can expect by using PMICs:

- **Configurability and flexibility:** Today's PMICs are flexible — one design can be used in multiple applications by making programming (firmware) updates. The default values, sequencing, and other parameters are all programmable. This decreases manufacturer time-to-market and bill-of-material.
- **Multiple output rails:** Today's PMICs are capable of low-, medium-, and high-voltage power levels. There are many individual voltage rails in one PMIC, as well as several buck, boost, buck-boost, LDOs, and load switches to perform many functions.
- **Small solution size:** PMICs are small and provide all the functionality in one package, which is an improvement over previously used individual discrete solutions.
- **Ease of customization:** Because the PMIC is configurable and programmable, the same device can be reprogrammed for several solutions. They're also configurable with several regulator device technologies.

- **Lower external component count:** PMICs are a complete solution, integrating the voltage regulation, and tuning into one package. This lower component count reduces design time, size, and cost.
- **Reduced design costs:** PMICs are a system-in-a-package solution. They decrease power source current consumption, decrease design time, lower component count, and deliver an optimized solution to customer without hardware customization.
- **High integration:** Other features like analog-to-digital converters (ADCs) and coulomb counters can be integrated into the PMICs to provide a reliable and easy way to monitor the power system and critical signals.
- **Reduce time-to-market:** PMICs allow customization without the need to design new hardware. With reliable and qualified components, the time-to-market can be significantly reduced for customers.
- **Reduced EMI:** The small size and integration inherently reduces EMI. A PMIC's configurability and optimized power MOSFETs also result in reduced EMI. This results in designs requiring less EMI troubleshooting, minimized shielding, fewer components, and quicker EMI certification.
- **Multiple uses:** PMICs can be used in many applications from integrated motor control, to battery management, modular power units, power loss protection devices, and DC-DC converters.

Highly Integrated Power Application Controllers (PAC™)