Design of
Power Management Integrated Circuits

Bernhard Wicht

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To my beloved family,
Sabine, Luise, Friederike, Konstantin,
and to my parents
Siegrid and Eberhard.

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Preface

In the March 2020 issue of the IEEE Solid-State Circuits Magazine, IEEE fellow Marcel Pelgrom writes in one of his excellent and inspiring Associate Editor's View columns entitled *Standing on Shoulders* about the timeless need for textbooks: "…where is the next disruptive view of our field, something that is desperately needed after this dazzling journey from 10-micron devices to nanometer electronics for quantum computing?" This book is my take on the field of power management.

The book delves into the fascinating world of power management IC design. This field has seen rapid growth in recent years, with the increasing demand for energy-efficient electronics, in particular, portable battery-operated devices. Power management integrated circuits are used for highly efficient power supplies and controlling power switches. It is incredible how these technologies have gained tremendous importance in making electronic solutions for global growth areas such as renewable energies, transportation, and communications more compact, energy-efficient, and reliable. Future machine learning and AI applications will only be possible with intelligent power management to supply complex processors and sensors.

I got into power management when I joined the industry in the early 2000s and went along a steep learning curve on all kinds of power management systems and design aspects. When I became a professor in 2010, I created a new course dedicated to power management IC design. However, no comprehensive textbook was available, and I had to rely on scientific papers and application notes.

A few years later, the idea of this book came up. Since then, I have been fascinated and challenged by the fast pace of progress and innovation in power management. The book provides a complete resource for those interested in power management IC design, covering basic concepts, advanced topics, and recent innovations in this rapidly evolving field. It is intended for students, educators, professors, and new and experienced engineers who want to learn about power management IC design, providing valuable insight and practical guidance for designing power management circuits and systems. Each chapter is organized to make it easy to find specific sub-topics, with numerous real-world examples illustrating key design concepts and techniques.

When I teach an entire course on power management IC design at a Master's or advanced Bachelor's level, I reduce the content and follow this outline: (1) Introduction (applications, challenges, physical implementation); (2) Linear Voltage Regulators; (3) Charge Pumps and Capacitive DC–DC Converters; (4) Power Transistors; (5) Gate Drivers; (6) Protection and Sensing; (7) Inductive DC–DC Converters; (8) Hybrid Converters. I also offer a design lab based on Spice simulation accompanying the lecture. Starting the class with the linear regulator right after the introduction allows the lab to begin early in the semester. I turned a lot of lab assignments and exercises into the many examples in this book (to my respected future students: I hope I'm not giving too much away.).

In his column, Marcel Pelgrom also writes about the burden of writing textbooks. And indeed, this book is the result of an investment of uncountable hours over several years. Writing a book also means that there will be missing content, on purpose but also by mistake. My fellow readers: Despite careful review, there will be mistakes, and I apologize in advance. Any feedback is highly appreciated. Please get in touch.

This book would not be in your hands without careful review, invaluable feedback, and encouragement by many people. I want to thank my former and recent Ph.D. students, in particular, Peter Renz (who read through the entire draft) and Tobias Funk, Saurabh Kale, Maik Kaufmann, Tim Kuhlmann, Jens Otten, Christoph Rindfleisch, and Jürgen Wittmann. Thanks to Markus Henriksen for his feedback on switched-capacitor (SC) and hybrid converters. Hartmut Grabinski ensured that Maxwell's equations were correctly applied to interconnections and printed circuit board (PCB) layout. Detlev Habicht and Niklas Deneke supported in capturing photographs for the book. I am grateful to the team at Wiley, in particular, to Sandra Grayson, Juliet Booker, Kavipriya Ramachandran, and Jeevaghan Devapal for their excellent support and patience. I wish to thank many more people.

Writing such a book is impossible without the support of my family. I want to thank my parents, Siegrid and Eberhard, who have supported my fascination with microelectronic circuits since I was nine. Thanks go to my children, who became real fans of my book project, even though they often had to take a back seat, especially when finalizing the manuscript over the last 1–2 years. I am indebted to my wife, Sabine. This book would not have been possible without her love and understanding.

Enjoy the exciting journey of exploring the design of power management integrated circuits!

August 2023, Gehrden *Bernhard Wicht*

1

Introduction

Power management integrated circuits (PMICs) are essential in today's electronic devices. They manage power delivery and consumption, provide efficient power supplies, and drive power switches that control actuators and motors, as illustrated in Fig. 1.1. PMICs can be integrated into complex integrated circuits (ICs) or implemented as dedicated ICs. In this book, the term PMIC will refer to any type of power integrated circuit.

The importance of PMICs has grown significantly in recent years, driving innovation and progress in various industries, from consumer electronics to automotive and industrial applications. With the progress of machine learning and artificial intelligence (AI), intelligent power management is critical to supplying complex processors and sensors.

PMICs have enabled the development of smaller, more energy-efficient, and reliable electronic solutions. They also play an essential role in environmental aspects and sustainability. By regulating the power supply of electronic devices, PMICs can reduce energy consumption and carbon emissions. Moreover, PMICs are crucial for the development of renewable energies, such as solar and wind power, by enabling efficient power conversion and management.

1.1 What Is a Power Management IC and What Are the Key Requirements?

A PMIC is an electronic component that delivers one or more supply voltages to other circuit blocks at a sufficient power level out of an electrical energy source, as shown in Fig. 1.1. The power conversion can happen in a linear way (usually the more straightforward method) or a switched-mode fashion, delivering energy portions at a specific frequency (usually the more energy-efficient approach).

The PMIC aims to utilize the energy source at maximum efficiency, while the input and output voltage may vary during operation. It also reacts to varying load currents from a few microamperes (standby) to several amperes (full-power operation).

The voltage conversion ratio is the relation V_{out}/V_{in} between the output and input voltage. The input voltage V_{in} can be greater or lower than the output voltage V_{out}, defining a step-down converter (buck converter) or a step-up converter (boost converter). Buck-boost converters allow V_{in} to vary over a wide range below and above V_{out}.

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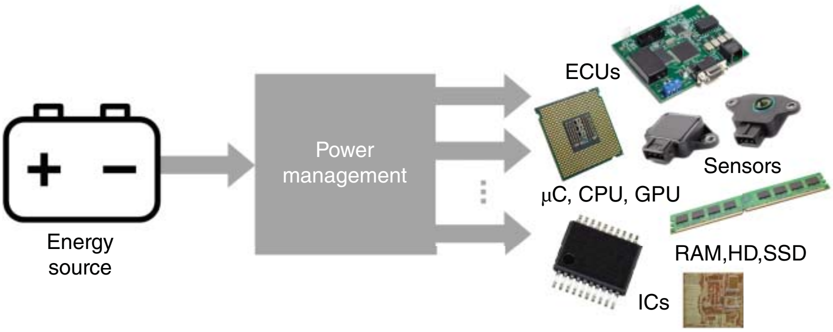


Figure 1.1 The role of power management: placed between the energy source and the electronics, it provides one or multiple supply voltages at the correct power level required by the application. Source: Brunbjorn/Adobe Stock; daniiD/Adobe Stock; Ruslan Kudrin/Adobe Stock; estionx/Adobe Stock.

The power conversion efficiency η (sometimes also called *PCE*) is defined as the ratio between the output power P_{out} delivered to the load and the input power P_{in} dissipated from the energy source,

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}}, \tag{1.1}$$

where P_{loss} accounts for the power dissipated within the power management circuit. It needs to be delivered from the input but does not contribute to the output power. We want to keep P_{loss} as low as possible. For $P_{loss} = 0$, the efficiency reaches its maximum, $\eta = 1$. It is common to express the efficiency in percent. In that case, we multiply Eqn. (1.1) by 100%.

PMICs typically include various features like voltage regulators, battery chargers, and power management control algorithms. They may also include monitoring and protection against overcurrent, overheating, and other failure cases. In some applications such as automotive, PMICs are alternatively called smart power ICs, emphasizing the combination of power devices with smart control and monitoring features, all integrated on a single chip.

One major trend is the increasing integration of PMICs. As more functions are combined onto a single chip, the resulting system becomes smaller, more efficient, reliable, and less expensive.

To summarize, the key requirements of PMICs are

- *Size, volume, footprint, and weight*: The PMIC, including external passive components, must often fit into a confined space like in smartphones or wearables. In portable devices, also the weight is critical. The lower weight is also crucial in automotive as it reduces gas and energy consumption.
- *Power conversion efficiency*: High efficiency means low losses. The lower the power losses, the longer the battery time. It also causes reduced heat and lower cooling effort, which, in turn, reduces the size and weight of the power management solution.
- *Reliability, no disturbances, and low noise*: PMICs are noise sources that may impact other sensitive electronic parts due to their switching nature. Handling high voltages and currents causes stress and reliability issues at the component, package, and assembly levels.
- *Cost*: Like most microelectronic products, there is always some pressure to reduce the cost of the IC and the overall bill of materials at the system level. Power management is not always considered a key differentiator. At the same time, physics cannot be cheated, and PMICs are a fastly growing market with good margins.

1.2 The Smartphone as a Typical Example

Looking at Fig. 1.2a), it is impressive to see how far mobile phones have come since the early 1990s. Back then, phones could only make voice calls and had a standby time of about a day or less. The picture is not to scale, but it was bulky and about 500 g in weight. It is incredible to think about all the features and functions that modern smartphones have today, illustrated in Fig. 1.2b). It is a remarkable example of the outstanding advancements in modern microelectronics. Today's smartphones are much smaller, lighter (typically 150 g), and more powerful. They have considerable computing power, 4K video capture, high-end gaming, virtual reality functions, and higher display resolution. This achievement in performance is thanks to ultra-low-power microelectronics and dedicated power management. Additionally, it is noteworthy that making a phone call is no longer the primary use case for these advanced devices.

Now we do what we usually do not want to; we drop our precious smartphone and look at the electronics inside. Figure 1.2c) shows a printed circuit board of the iPhone 13. The entire electronics is implemented on a layered motherboard sandwich of which Fig. 1.2c) shows a major part. The white frame boxes indicate some of the many PMICs inside the phone. There are more PMICs on the reverse side and other printed circuit board (PCB) parts, including ICs for the audio amplifier and wireless charging. PMICs are a considerable part of the smartphone. Connected to the Li-ion battery with a typical cell voltage of 3.7 V, multi-phase DC–DC converters supply the application processor that comprises multicore CPU and GPU blocks. The voltage levels are dynamically scaled in the range of typically 0.25–1.5 V at load currents of more than 10 A (see dynamic voltage and frequency scaling in Section 1.7). The typical power consumption is in the range of a few watts. In comparison, desktop PC processors dissipate more than 100 W. Running at high switching frequencies of tens of MHz, the voltage converters achieve small size, ultralow profile, and near-load integration at high conversion efficiency. No active cooling is required.

Looking closely, we identify hundreds of tiny passive components surrounding the ICs, mainly capacitors and inductors. As they are energy-storing components, their size can be reduced by decreasing the storing times, in other words, by increasing the switching frequency of the power conversion. It defines one of the leading research goals of today's power management solutions – achieving faster switching while keeping the conversion efficiency high. We will continuously address this topic throughout this book.

Figure 1.2 a) The mobile phone in the early 1990s, b) the smartphone today, and c) the electronics of the iPhone 13 with PMICs marked by white boxes. Source: a,b) aquatarkus/Adobe Stock; c) ifixit.

1.3 Fundamental Concepts

There are different ways to implement DC–DC converters that convert an input DC voltage to another voltage level. To keep it more practical, we consider a scenario of how to convert 12 to 2 V.

1.3.1 Using a Resistor – The Linear Regulator

We can use a simple resistor to convert 12 to 2 V, as shown in Fig. 1.3. For a load current of 1 A, a resistor of 10 Ω results in $V_{out} = 2\,\text{V}$. In reality, the resistor is replaced by a controlled transistor such that its conductance is adjusted depending on the operating conditions like input voltage and load current. This approach works very well. However, the voltage drop between input and output is converted into heat. That is why there is significant power dissipation in the resistor, $10\,\text{V} \cdot 1\,\text{A} = 10\,\text{W}$ in this example. The power loss is even larger than the output power $P_{out} = 2\,\text{W}$. In terms of energy efficiency, this concept has a significant drawback.

Nevertheless, it is the fundamental principle of a linear voltage regulator and, by far, the most used power management circuit today. On the positive side, besides its simplicity, it gives a “clean” output voltage with a fast transient response.

Without the excessive losses, there would be no need for alternative power conversion concepts, as discussed in Sections 1.3.2–1.3.4 below. The lower the voltage drop across the resistor (the controlled transistor), the lower the power loss. For this reason, linear regulators are often called low-dropout regulators with the widely used short-term LDO. Chapter 7 is dedicated to linear regulators.

1.3.2 Using Switches and an Inductor – The Inductive DC–DC Converter

To overcome the limited efficiency of the linear regulator, we again ask the question, how can we convert 12 to 2 V? We now use switches as shown in Fig. 1.4a). The switches are combined with an inductor, forming an inductive DC–DC converter as a typical switched-mode power supply (SMPS) implementation. As there is no resistive element in the power path, this concept has the potential to achieve much higher power conversion efficiency compared to a linear regulator.

The operation is as follows: The two switches turn on periodically in a complementary way. They are connected to the so-called switching node. The voltage V_{sw} at that node sees a square wave with an amplitude equal to V_{in} (12 V in this case), as shown in Fig. 1.4b). The switching node feeds into an L-C low-pass with two functions: filtering and energy storing. The filtering characteristic provides the average V_{sw} at the converter’s output. The average corresponds to the area under the switching node transient curve. Hence, V_{out} is a DC voltage; see Fig. 1.4b). By changing the on-time t_{on} of S1, the area under the square wave, and, consequently, the level of V_{out} can be varied. This concept

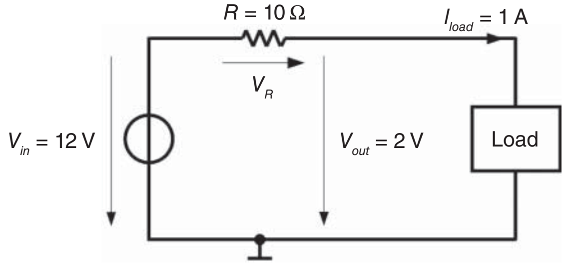


Figure 1.3 Conversion of 12 to 2 V by a simple resistor. This is the concept of a linear voltage regulator.

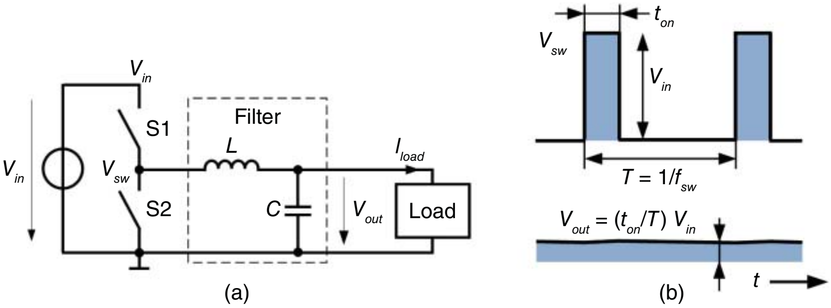


Figure 1.4 Voltage conversion using switches and an inductor L achieving high conversion efficiency: a) the fundamental step-down converter; b) waveforms of the switching node voltage V_{sw} and the output voltage V_{out}.

is called pulse-width modulation (PWM), the most popular control method in DC–DC converters. The duty cycle D defines the ratio between the on-time and the period time,

$$D = \frac{t_{on}}{T}. \tag{1.2}$$

For the step-down converter in Fig. 1.4, the duty cycle determines the voltage conversion ratio:

$$\frac{V_{out}}{V_{in}} = D = \frac{t_{on}}{T} \tag{1.3}$$

There are other topologies of DC–DC converters that have different conversion ratios.

The energy-storing characteristic of the L-C network is required in two ways. If S1 is turned on (S2 is off), energy is brought into the system. The capacitor C buffers V_{out} in case of varying load currents (load transients). C is called a bypass capacitor because it bypasses the actual regulator during instantaneous load steps before the control loop can respond. Alternatively, C is referred to as the output buffer capacitor. The inductor L delivers the load current if S1 is active and in the second switching phase when S2 turns on (S1 is off). Due to the switching nature of the DC–DC converter, there will always be some finite output voltage ripple. It is a significant disadvantage compared to linear regulators (Section 1.3.1). The ripple can be reduced by enlarging L and C at the expense of larger size and reduced power density. Another way of reducing the ripple and, at the same time, increasing the output power is to use multiple parallel DC–DC converters. Such multi-phase converters operate in a time-interleave scheme, delivering multiple energy packages during each cycle.

When discussing energy efficiency, it is essential to note that in a steady state, there should be no power loss P_{loss} at a switch. If the voltage across the switch is V and the current through the switch is I, the loss is $P_{loss} = V \cdot I$:

$$\text{Switch turned on: } V = 0, I = I_{load} \rightarrow P_{loss} = V \cdot I = 0 \tag{1.4}$$

$$\text{Switch turned off: } V = V_{max}, I = 0 \rightarrow P_{loss} = V \cdot I = 0 \tag{1.5}$$

V_{max} is the (maximum) blocking voltage of the switch, which is equal to V_{in} in Fig. 1.4a). The relationship in Eqns. (1.4) and (1.5) is the fundamental reason, why switched-mode operation is widely used in power electronics. In actual designs, there will be various loss contributions, such as the finite on-resistance of the switches. There will also be switching losses and losses in the passive components. However, these losses are usually much lower compared to a linear regulator introduced in Section 1.3.1. Conversion efficiencies of more than 90% can be achieved. Chapter 10 covers inductive DC–DC converters comprehensively.

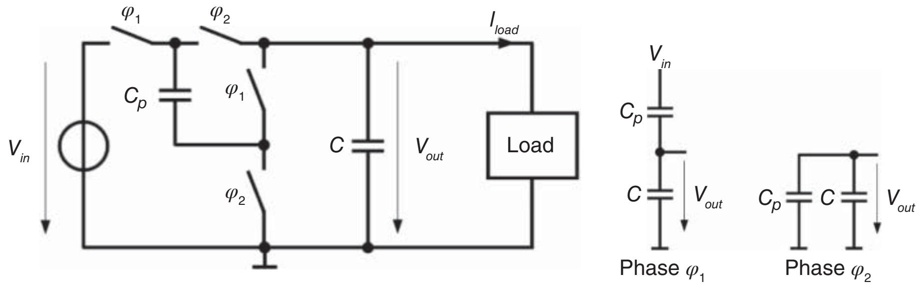
1.3.3 Switches and Capacitors – The SC Converter

Another way of voltage conversion is the combination of switches with capacitors. This concept has become very attractive for highly integrated power management designs due to the availability of high-density integrated capacitors in advanced CMOS technologies. Figure 1.5 shows a typical circuit along with the equivalent circuits in the two switching phases. During phase φ_1, both capacitors are connected in series to V_{in}. The capacitors are parallel in phase φ_2. The circuit periodically changes from a series to a parallel configuration, reducing the output voltage to half of the input voltage. Interestingly, this behavior is independent of the actual capacitor values. Their values determine the amount of charge shared between switching cycles, but in steady state, V_{out} will be exactly half of V_{in}. Note that ideally, no losses have occurred so far.

How can we convert 12 to 2 V? We can use two conversion stages. The first results in 6 V, the second one gives 3 V. How do we get to the target value of $V_{out} = 2$ V? We take advantage of the fact that C_1 can deliver only a limited charge. In other words, we let the load current discharge the output capacitor C until V_{out} reaches exactly 2 V. Most easily, this can be achieved by adjusting the clock frequency. Unfortunately, this is when the SC converter introduces power loss due to charge redistribution ($\sim CV^2$). The output voltage drop from 3 to 2 V can be seen as a voltage drop across an equivalent output resistance. Significant research has been dedicated to finding improved SC converter topologies and control mechanisms that minimize these losses. SC converters are further explored in Chapter 9.

1.3.4 Switches and Capacitors and Inductors – The Hybrid Converter

This approach takes the SC converter of Fig. 1.5 and adds an inductor, as illustrated in Fig. 1.6. The combination of L and C leads to the name hybrid converter. It utilizes the benefits of the inductive and capacitive conversion concepts presented in Sections 1.3.2 and 1.3.3. Two mechanisms help improve conversion efficiency. The inductor ensures soft charging of the capacitor, which



(a) (b)

Figure 1.5 Voltage conversion using capacitors: a) the fundamental switched-capacitor voltage converter; b) the equivalent circuits in phases φ_1 and φ_2, alternating between series and parallel configurations.

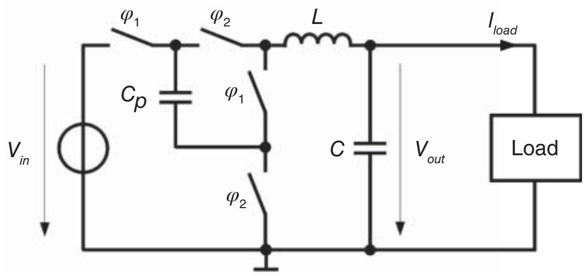


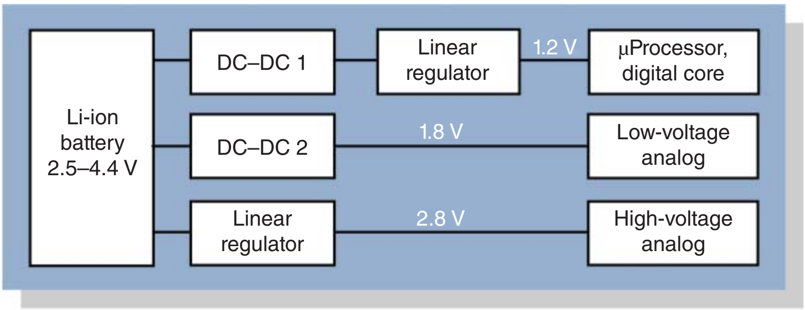
Figure 1.6 A hybrid converter formed by adding an inductor L to an SC converter resulting in higher conversion efficiency.

eliminates charge redistribution losses and minimizes the equivalent output resistance. L and C also form a resonant tank, which can achieve zero-current switching of the power switches. This way, the switching losses can be significantly reduced. On the downside, this concept has higher complexity than an inductive or capacitive converter. However, handling complexity is one of the great benefits of advanced microelectronics. Chapter 11 covers hybrid DC–DC converters comprehensively.

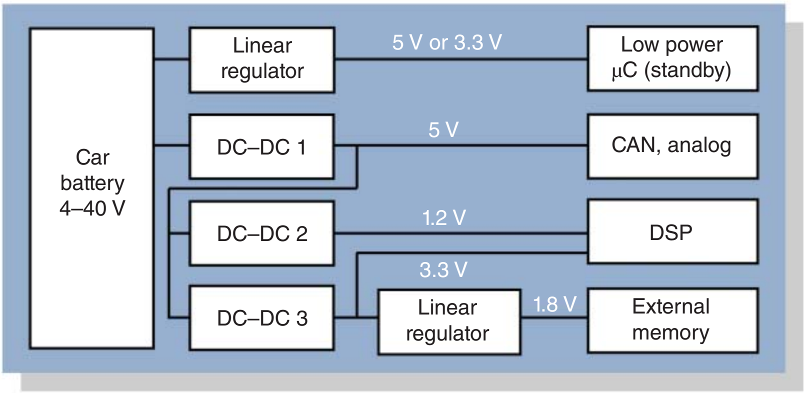
1.4 Power Management Systems

Electronic systems usually do not require only one supply voltage. Instead, various functional blocks have different supply voltage and power requirements. Figure 1.7 shows two examples of power management systems. Dedicated converters are assigned to supply each block at the point of load (PoL). State-of-the-art power management systems comprise multiple PoL regulators and DC–DC converters to supply microcontroller units (MCU), processors (CPU, GPU, and DSP), as well as analog and mixed-signal circuits.

In space-constraint applications such as smartphones, multiple voltage regulators are implemented in a single IC to minimize their footprint. Known as the multirail power supply (MRPS), it is the leading PMIC type with a market share of 20% (see Section 1.9).



(a)



(b)

Figure 1.7 Point-of-load (PoL) power management systems: a) handheld devices operating from a Li-ion battery have lower step-down ratios as compared to b) automotive, industrial, and data center applications that operate from a higher supply voltage like a car battery.

For large step-down ratios, linear regulators are not efficient. However, switched-mode DC–DC converters may not fulfill strict supply ripple and noise requirements for sensitive analog circuits such as sensor front ends. Hence, various conversion stages are combined, as illustrated in Fig. 1.7.

Combining a DC–DC converter as a first conversion stage with a subsequent linear regulator (LDO) is beneficial. The DC–DC converter guarantees high efficiency, while the LDO ensures a “clean” output voltage with a fast transient response. If the intermediate voltage V_{mid}, provided by the DC–DC converter, is close to the target output voltage, the linear voltage regulator will also show an acceptable efficiency. We can calculate the overall efficiency by multiplying the efficiency values of each stage:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{mid}} \cdot \frac{P_{mid}}{P_{in}} = \eta_1 \cdot \eta_2 \tag{1.6}$$

For a large step-down ratio, i.e., if V_{in} is much greater than V_{out}, achieving high efficiency will be more challenging.

As illustrated in Fig. 1.7a), a Li-ion battery typically supplies portable devices such as smartphones and wearables with a voltage range of 2.5–4.4 V. There is a moderate step-down ratio. The automotive application shown in Fig. 1.7b) operates from a 12 V lead-acid battery. The board net voltage can vary a lot, for instance, from 4 to 40 V. Hence, the step-down ratio is much larger than in devices supplied by a Li-ion battery. A step-up converter (boost converter) is typically inserted that kicks in if the board net drops toward 4 V and stabilizes the input voltage of the subsequent stages to typically 10 V (not shown in Fig. 1.7b) for simplicity). This way, the power management system can still provide 5 V at the output.

1.5 Applications

The application defines the energy source on the left of Fig. 1.1 with several examples shown in Fig. 1.8. Consequently, the applications also determine the system voltages, which are the power management input voltages. There is a trend toward higher voltages, as discussed in the following subsections, motivated by higher energy efficiency. For the same reason, the IC-level voltages of the electronics on the right of Fig. 1.1 scale into the opposite direction and reach levels of 1 V and lower. More details on IC-level supply voltages follow in Section 1.6. We discuss various applications below, starting with the lowest voltages at the bottom left of Fig. 1.8.

1.5.1 IoT Nodes and Energy Harvesting

Internet-of-Things (IoT) wireless nodes, installed in smart homes and office spaces and used in an industrial environment, are often designed with 10-year battery lifetime targets [1]. To prolong the life of a 3 V-CR2032 coin cell, the average current needs to be kept below 2.5 μA (7.5 μW). However, this can be challenging since the wireless node draws around 5 mA when it is in active mode (transmit). Several blocks contribute to this average power dissipation, including the CPU, the transceiver, sensors, and power management. Fortunately, continuous operation is not required, and duty cycling reduces the average current consumption to typically 6 μA. The sleep current in the order of 1 μA consists of leakage current, memory retention, analog circuits, such as a power-on reset, and a low-frequency sleep clock.

Energy harvesting can be used to expand the battery time. The ultimate goal is to remove the battery at all. In addition to the positive environmental impact, it can significantly reduce maintenance effort and cost. Besides the IC, the battery is the most expensive part of the wireless sensor

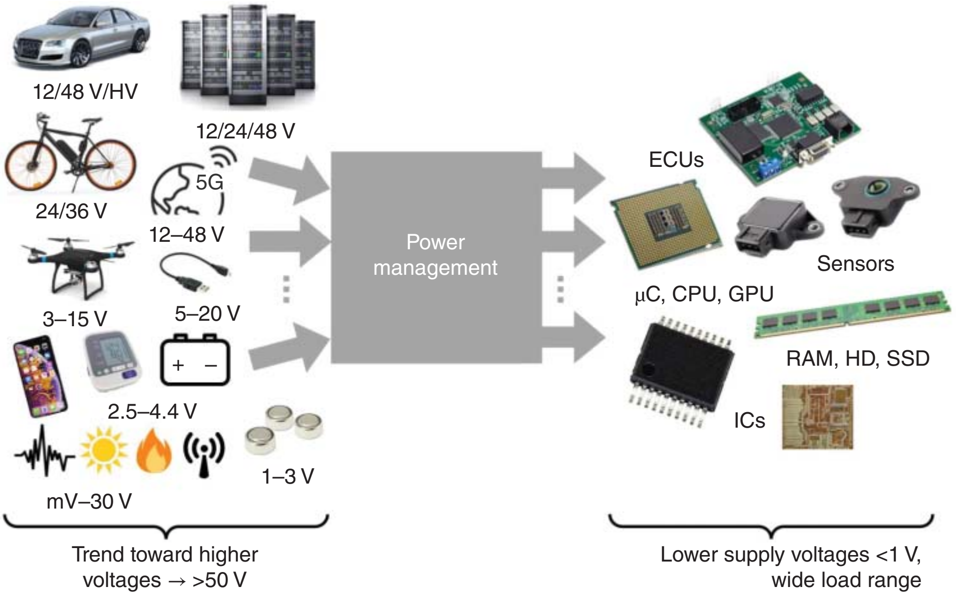


Figure 1.8 The system voltages in various applications define the input voltage for the power management circuits. On the load side, the supply voltages follow the trend of decreasing supply voltages toward 1 V and below with a wide load current range. Source: dezign56/Adobe Stock; ifeelstock/Adobe Stock; Pawinee/Adobe Stock; Scanrail/Adobe Stock, kornkun/Adobe Stock.

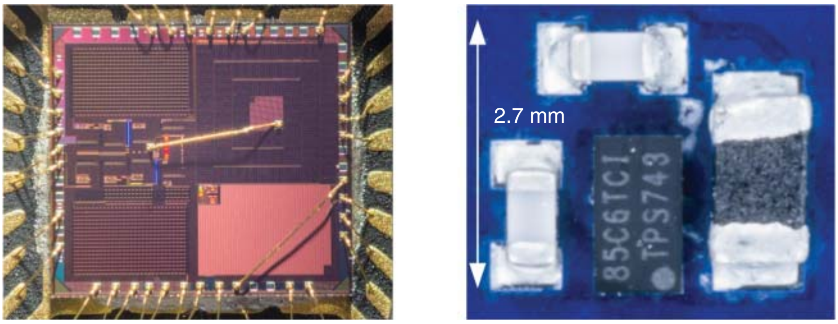
node (about 20% [1]). With the decreasing cost of the IC, the battery cost is expected to contribute a growing percentage of the total node cost over time.

Energy harvesting converts mechanical energy (kinetic energy and vibration), light (via solar cells), thermal energy, and the energy of radio frequencies (RFs) into usable voltages. RF energy harvesting is the lowest cost option, but the available power levels are the lowest. Hence, a promising approach is multisource energy harvesting. Nevertheless, the typical output power is in the order of 1 mW and below.

Power management circuits in energy harvesting applications operate from very low voltages in the millivolt range and even below. Charge pumps or similar techniques bring these low input levels to an intermediate voltage of ~0.5–1 V, just above the transistor threshold voltage. At this point, another step-up DC–DC converter (inductive or capacitive) kicks in. It boosts this voltage to 1.8 V, for instance, suitable for supplying functional electronic blocks. Once the voltage reaches the power-on reset level, the IoT node transmits a data packet and shuts off until enough power is available again.

1.5.2 Portable Devices, Smartphones, and Wearables

Many designs run from low-voltage batteries (button cells) in the range of 1–3 V. Li-ion batteries with a cell voltage of 2.5–4.4 V have become the primary battery technology for portable devices like laptops, mobile phones, and wearables. Laptops use two or three battery cells in series to supply input voltages of 7.4 or 11 V. Smartphones are covered as the introductory example in Section 1.2. The growing field of wearables includes applications like smartwatches, fitness trackers, smart headphones, glasses, medical monitoring devices, and implants. The power consumption of wearables is typically a few hundred milliwatts, an order of magnitude lower than a smartphone. It



(a) (b)

Figure 1.9 Miniaturized DC–DC converters for wearables: a) a fully integrated PMIC with on-chip integrated passives. Source: Peter Renz et al. [2]/from IEEE; b) A DC–DC converter in a 1.6 mm × 0.9 mm, 8-ball wafer-level chip-scale package (WCSP) with discrete passives (TPS627431, Texas Instruments). Both photographs are depicted to scale. The size of the objects in the photographs is represented in relation to one another.

benefits from a smaller display with fewer pixels and a scaled-down CPU that runs at a lower frequency.

PMICs for portable devices must provide high power conversion efficiency to ensure long battery times. As the primary requirement, the PMIC designs need to be ultracompact and lightweight in addition to providing high power conversion efficiency. These advantages are achieved by fast-switching DC–DC converters with miniaturized passive components (see Section 1.8.3 and more details on integrated passives in Chapter 4).

Figure 1.9 shows two PMIC examples for wearables. Figure 1.9a) is a hybrid DC–DC converter with fully integrated passives [2]. The output buffer capacitor has a capacitance of 10 nF (lower right corner of the die photo), and the inductor is a square spiral coil of 9 nH (upper right, see Fig. 4.10 for an enlarged picture). Due to these small values, the converter operates at switching frequencies of up to 47.5 MHz. The power management circuits support low quiescent currents during sleep modes (power levels <25 mW) to achieve high efficiency and long battery times. The DC–DC converter in Fig. 1.9b) fits in a wafer-level chip-scale package (WCSP). The device is optimized to operate with a 2.2 µH inductor and 10 µF output capacitor, operating at 1.2 MHz. It offers ultralow quiescent current of typically 360 nA. Despite the compact design, the DC–DC converters in Fig. 1.9 reach peak efficiencies of more than 85% and 95%, respectively.

Example 1.1 *We want to estimate the battery time of a smartwatch supplied by a Li-ion battery of* 270 mAh. *The battery voltage of* $V_{bat} = 3.6\,\text{V}$ *is converted to* $V_{out} = 1.8\,\text{V}$ *to supply the internal electronics at an output power of* $P_{out} = 100\,\text{mW}$. *We distinguish two types of voltage conversion: a) an LDO (linear regulator) with an efficiency of 50%; b) a hybrid converter with an efficiency of 85%.*

With an efficiency of less than 100%, the input power P_{in} *will be higher than* P_{out}. P_{in} *determines the current drawn out to the battery. From Eqn. (1.1), we obtain for case a)*

$$P_{in} = \frac{P_{out}}{\eta} = \frac{100\,\text{mW}}{0.5} = 200\,\text{mW}, \tag{1.7}$$

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{200\,\text{mW}}{3.6\,\text{V}} = 56\,\text{mA}. \tag{1.8}$$