1.15(b)], one cell is overdischarged down to 1.5V, while the other ones are around 3.5V. Despite the fact that the total voltage is 12V, three of the cells in this battery are not fully discharged, and one of its cells is being damaged. Therefore, a system that relies on the total battery voltage to determine when to stop discharging the battery (such as a motor controller with a low voltage cutoff) gives the user a false sense of security; that system will overdischarge some cells, damaging them. It is therefore essential that a BMS monitor such a battery to prevent any cell from being overdischarged and damaged.

1.3 Li-Ion BMSs

In the previous sections we saw how abusing Li-Ion cells may reduce their life, result in damage, and can even be a safety issue. Having analyzed the problems with Li-Ion cells, let us look at Li-Ion BMSs for solutions. It is the job of a BMS is to ensure that the cells in a battery are operated within their SOA. This is particularly important for large Li-Ion battery packs because:

- Li-Ion cells are so much more unforgiving of abuse than other chemistries.
- Large battery packs, with many cells in series, are more prone to be charged and discharged unevenly due to unbalance among cells. Li-Ion cells must not be overcharged or overdischarged.
1.3.1 BMS Definition

There is no unique definition of what a BMS is and does, and sometimes other terms [such as voltage management system (VMS) or protection circuit module (PCM)] are used for what is in effect a BMS. Here I take the wide view that a BMS is any product or technology used with the intent of taking care of a battery in one way or another. This may include any of the following functions:

- To monitor the battery;
- To protect the battery;
- To estimate the battery’s state;
- To maximize the battery’s performance;
- To report to users and/or external devices.

1.3.2 Li-Ion BMS Functions

For the sake of safety, and for the sake of the cells, a Li-Ion BMS must, at the very least (in order of importance), do the following:

- Prevent the voltage of any cell from exceeding a limit, by stopping the charging current, or requesting that it be stopped. This is a safety issue for all Li-Ion cells.
- Prevent the temperature of any cell from exceeding a limit by stopping the battery current directly, requesting that it be stopped, or requesting cooling. This is a safety issue for Li-Ion cells that are prone to thermal runaway.
- Prevent the voltage of any cell from dropping below a limit by stopping the charging current or requesting that it be stopped.
- Prevent the charging current from exceeding a limit (which varies with cell voltage, cell temperature, and previous level of current) by requesting that the current be reduced or stopped, or by stopping the current directly.
- Prevent the discharging current from exceeding a limit, as described in the previous point.

A BMS is essential when charging a Li-Ion battery. As soon as any cell reaches its maximum charged voltage, it must turn off the charger (Figure 1.16). A BMS may also balance the battery to maximize its capacity. It may do so by removing charge from the most charged cell until its voltage is low enough that the charger may come back on and give the other cells a chance to be charged. After many cycles of this process, all the cells will be at the same voltage, fully charged, meaning that the pack will be balanced. A BMS is also essential when discharging a Li-Ion battery. As soon as any cell reaches a low cutoff voltage, it turns off the load (Figure 1.17).

1.3.3 Custom Versus Off-the-Shelf

A major goal in this book is to help you decide whether you should use an off-the-shelf or custom BMS. There are a few specific needs that can only be met by a custom BMS: the need for intellectual property (IP) or tight specifications. Other-
wise, a commercially available BMS will get you there much faster for much less money, with fewer resources and a higher likelihood of success. Simply put:
• **Custom:** you own, you control;  
• **Off-the-shelf:** fast, easy, cheap.

Entities that will probably benefit from a custom design include:

• Big auto manufacturers who need full control over their products;  
• Large electronics corporations who want to enhance their product line;  
• Companies poising themselves for acquisition, and wishing to increase their perceived value;  
• Hobbyists who want the learning experience.

Conversely, these entities will probably benefit from using an off-the-shelf product:

• Companies designing EV, PHEV, and HEV passenger cars;  
• Small to medium manufacturers of specialized vehicles (utility, heavy duty, public transportation);  
• Design services companies and engineering consulting firms;  
• Vehicle integrators;  
• Companies developing land-based back-up systems, utilities;  
• Cell manufacturers and battery assembly houses;  
• EV converters;  
• Efficient companies that are results driven.

Certain cell manufacturers sell a BMS together with their cells (see Section 4.1.3). Their BMS is not available by itself, and, in some cases, the cells are not available by themselves. If using such cells, the cell manufacturer is in effect making the custom versus off-the-shelf choice for you.

Please consider carefully the pros and cons of designing your BMS (Figure 1.18) before you embark on such project, lest you should end up saying: “I wish I had known how complex this was going to be before I started!”

### 1.4 Li-Ion Batteries

#### 1.4.1 SOC, DOD, and Capacity

The state of charge (SOC) of a cell or a battery at a given time is the proportion of the charge available at that point, compared to the total charge available when it is fully charged. It is expressed in percent, from 100% when full to 0% when empty. The SOC evaluation function is also known as the *fuel gauge*, especially in EVs, because of its analogy to a gas car’s fuel gauge. It is essential to understand that each cell in a battery has its own SOC, and that the battery itself has its own, separate SOC.

The depth of discharge (DOD) of a cell or battery is a measure of the charge removed from it. It is expressed in amp-hour (Ah). DOD can be expressed in a percentage as well, and is commonly done so in Lead Acid batteries. It is really more