How to Charge a Battery

Varieties of rechargeable batteries and their charging strategies

By **Dr Thomas Scherer** (Germany)

Knowledge among technical folk about rechargeable batteries and how to charge them properly can often be rather sketchy. And the situation among non-technical folk is even worse, with myths, hearsay and bizarre assumptions being perpetrated left, right and center. All this is despite the fact that rechargeable batteries are a part of many aspects of everyday life, and that most of us have the Internet at our fingertips as a potential source of accurate information. In this article we try to bring together the most important facts.

Fifty years ago the subject of rechargeable batteries did not have the importance it has today. Mostly they were found in cars (sometimes called 'accumulators') to operate the on-board electric starter motor to get an internal combustion engine going using stored electrical energy. But apart from that, in everyday life it was rare to encounter an electrically-operated device that was powered from rechargeable (or 'secondary') cells. For your transistor radio or flashlight, which were the main portable devices available at the time, you would use primary cells, usually based on a zinc-carbon chemistry, or, later, on the superior alkaline manganese dioxide chemistry.

Then things started to move quickly. The 1980s saw a rise in popularity of nickel cadmium (NiCd) rechargeable batteries in sizes compatible with primary cells (in particular in AA size),

Figure 1. Gel lead-acid battery rated at 12 V and 4.5 Ah. Batteries of this type are found in applications such as warning lights used around roadworks.

Figure 2. Inside the battery of my old Prius II hybrid vehicle: 28 modules each comprising six Panasonic prismatic NiCd cells rated at 1.2 V and 6.5 Ah wired in series, giving a total of 201.6 V. The pack can store 1.3 kWh and weighs in at 39 kg.

and, as you might expect, many circuit ideas and construction guides were published for NiCd chargers. Despite their slightly lower nominal terminal voltage it was easy to use these cells to replace disposable primary cells and so save a useful amount of cash. Come the 1990s, NiCd rechargeables started to be replaced by the easier-to-use nickel metal hydride (NiMH) cells, and since 2017 NiCd cells are practically banned in Europe, and can no longer be purchased except for special applications.

Also electronic devices were becoming more and more portable. On the heels of Sony's Walkman (for the benefit of younger readers: a portable cassette player) came MP3 players, laptops started to replace desktop PCs, telephones became mobile and suddenly everyone could have a smartphone to do their computing on the move. Most recently bicycles and, increasingly, cars have begun to go electric. All these devices, and many more besides, need batteries, and the range of different battery types available and their characteristics are as diverse as the range of applications.

Types of rechargeable battery

First some terminology. The word 'battery' comes to us via a French word meaning an array of artillery weapons, to which Benjamin Franklin compared his experimental array of Leyden jars. So strictly speaking a 'battery' should comprise more than one cell, but this distinction is only rarely made in everyday usage. The English term 'battery' covers both rechargeable and non-rechargeable types, the more precise terms 'primary cell', 'secondary cell' and 'accumulator' no longer being in common use. Now, with that out of the way, we can look at some of the more common battery types used today.

At over 160 years old, the **lead-acid battery** (see **Figure 1**) is certainly the oldest type of rechargeable battery that still finds practical use. The cells, which typically have a nominal voltage of 2 V, have been used in automobiles since around 1900. In that year the celebrated Lohner-Porsche Semper Vivus [1] was unveiled, the first ever hybrid car (are you listening, Toyota?). Another early application was in telephone and telegraph offices. The lead-acid battery is still difficult to beat in terms of price and robustness, and so, despite its heavy weight and other disadvantages it is still used to power the starter motor for internal combustion engines.

The **NiCd battery** (see the example from a hybrid car in **Figure 2**) also has a long history, going back over 100 years. In particular, in the 1980s, small NiCd cells were the most popular rechargeables for powering consumer electronic devices despite their nominal voltage of only 1.2 V. Their ability to deliver large currents made them the battery of choice for cordless tools and radio-controlled models. Also, Toyota Prius models up to and including the Prius III use this battery technology for their hybrid drive. The biggest disadvantages are poor environmental credentials (cadmium is toxic) and the notorious 'memory effect'.

The better is the enemy of the good: low-cost **NiMH batteries** (see **Figure 3**) came to replace NiCd batteries in consumer devices, having first been manufactured on an industrial scale some 35 years ago. Offering the same nominal voltage of 1.2 V they were an ideal substitute. They are also by and large more environmentally friendly, do not exhibit the memory effect, have reasonable energy density and are economical. On the other hand, they are a bit trickier to charge. Since about ten years ago NiMH batteries with very low self-discharge have been available.

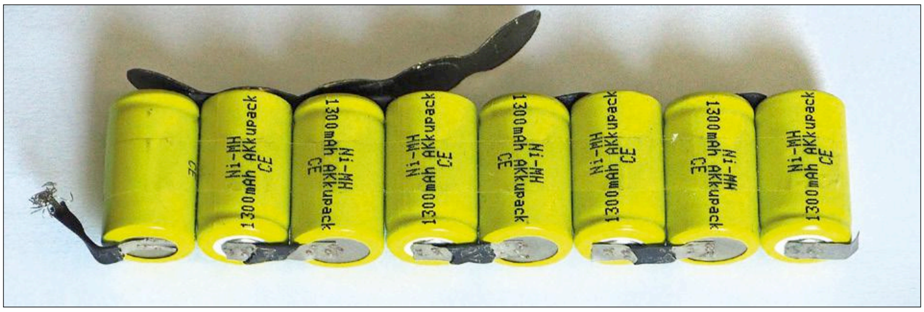

Figure 3. NiMH pack from a handheld vacuum cleaner that has seen better days. The cells are welded together and (used to) provide 9.6 V with a capacity of 1.3 Ah.

Figure 4. Type 5s1p Lithium polymer battery rated at 18.5 V and 5 Ah. The maximum discharge current is 15 C, or 75 A, and the pack is designed for use in radio-controlled models. The small six-way connector allows a charge balancer to be connected.

Figure 5. This typical lithium battery in 18650 format is based on an $LiCoO_2$ chemistry. Such cells are becoming more popular in flashlights and especially in solar garden lights. The nominal voltage is given as 3.7 V rather than 3.6 V.

Figure 6. The 45-V LiFePO4 pack from my Segway clone: 14 type 38120 cells rated at 9 Ah and 10C. In the foreground is the charge balancer.

More recent rechargeable battery technologies are based around the element **lithium**. These chemistries allow the construction of lightweight batteries with a very high energy density, which are important factors in mobile applications such as laptops, tablets and smartphones as well as in electric vehicles. The three main types of practical importance are as follows: **LiPo** ('lithium polymer': see **Figure 4**) whose compactness makes them ideal for mobile applications; and **$LiCoO_2$** (see **Figure 5**) and **$LiFePO_4$** (see **Figure 6**) for electrical drives. Their nominal voltages, at 3.7 V for LiPo, 3.6 V for $LiCoO_2$, and 3.2 V for $LiFePO_4$, are significantly different from those of other chemistries. They do not exhibit the memory effect and have very low self-discharge. On the other hand they are sensitive to environmental conditions and there are strict rules to obey when charging and when discharging them. As well as a range of cylindrical formats lithium batteries are available in customized packs for mobile devices and in prismatic housings with higher capacity. It is interesting to note that the current range of Tesla electric vehicles use 'batteries' comprising many thousands of type 18650 cylindrical cells. The **RAM** (rechargeable alkaline manganese) battery (AA size shown in **Figure 7**) is certainly the newest kid on the block in the world of rechargeable batteries. These alkaline secondary cells have a nominal voltage of 1.5 V and so are ideal as direct replacements for zinc-carbon or alkaline manganese primary cells. However, they are only suitable for use in applications with low discharge current, must not under any circumstances be subjected to deep discharge, and require a special charger: they are decidedly not compatible with NiCd or NiMH chargers!

Table 1 shows a list of the above rechargeable battery types with additional information such as the expected number of charge-discharge cycles (to the point where the cell's capacity falls to 75 % or 80 % of its original value) and the energy density (more precisely, the 'specific energy'), which is an important figure of merit in many applications. We will not look here at other battery technologies that are not found in everyday commercial applications or at technologies still at the research stage, or at large-scale energy storage units such as flow batteries.

Charging strategies

It is a good idea not just to pay attention to, but to follow to the letter the advice given by the a battery's manufacturer with regard to operating conditions (and in particular maximum discharge current) and to make sure that you respect the maximum permissible charge current. Nevertheless, for each type of battery there are some general properties that we can remark on, and we can compare the various allowable and optimized charging strategies. The most important considerations are the ability to withstand deep discharge and overcharging, the charge current limit and the details of the charging strategy; we will also look at aspects such as self-discharge rate and the degree to which the battery suffers from the memory effect.

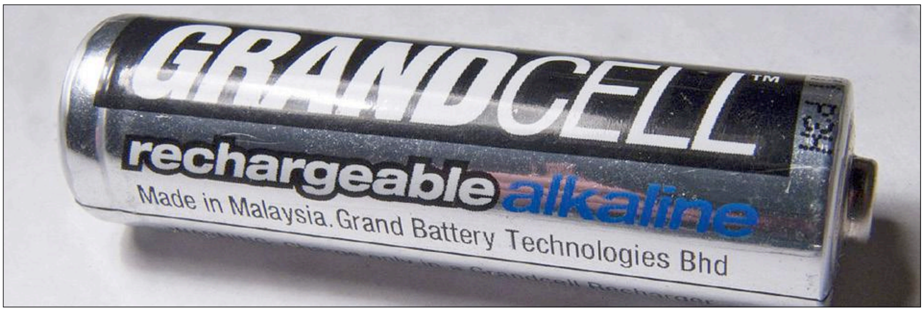

Figure 7. RAM battery cell based on an alkaline manganese chemistry in a standard AA package. These batteries must not be subjected to deep discharge and require a special charger.

Lead-acid batteries: In the case of sealed gel lead-acid batteries as well as the so-called 'maintenance-free' starter batteries it is important to ensure that they are not overcharged, as otherwise they can outgas. This can lead to a loss of electrolyte, which it is not a straightforward job to replace, and consequently to a shortening of service life and a reduction in capacity. In non-sealed lead-acid batteries, as used, for example, in fork-lift trucks, this is less of a problem as they can be topped up with distilled water. Lead-acid batteries should also not be subjected to deep discharge: the cell voltage should not be allowed to fall below 1.75 V. Relevant for storage is the self-discharge rate of 2% per month or more: for example, a starter battery on a petrol lawnmower may well not make it through the winter without some attention in January. The normal charging procedure is to begin with a constant current until the cell voltage reaches 2.35 V and then switch to constant voltage charging until a minimum current threshold is reached. Unless indicated otherwise the charge current should be at most 0.1 *C* (that is, 10% of the rated capacity in Ah/h). The current threshold when charging stops is typically 0.01 *C*.

In the case of a typical 12 V starter battery rated at 60 Ah this means that charging begins at a constant current of at most 6 A, and then, when the battery voltage reaches 14.1 V, the charging voltage should be kept constant. The current will then fall and when it reaches 0.6 A charging can stop. Continuing to charge at this point ('trickle charging') does not cause any problems. **Figure 8** shows a typical charging curve for this type of battery using the **CC/CV strategy** ('constant current/constant voltage').

A feature of lead-acid batteries is that over time they can lose capacity owing to a process called sulfation. To mitigate this special chargers are available that as well as providing a maintenance charging current, also provide regular millisecond-long pulses of current at over 100 A. This acts to prevent the formation of crystals in the battery and even help to break them down. A number of circuits along these lines have appeared in *Elektor* in the past.

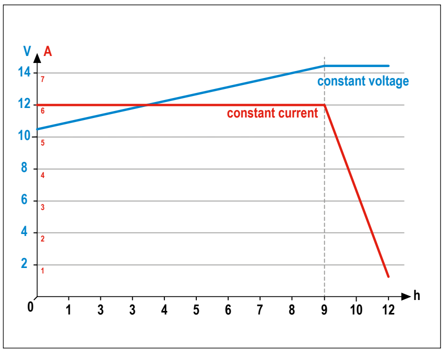

Figure 8. Idealized curves for CC/CV charging of a 12-V car battery rated at 60 Ah. The curves for lithium batteries are similar in appearance.

Table 1. Varieties of rechargeable battery.

Type	Nominal voltage	Cycle life	Energy density	Applications
$LiCoO_2$	3.6 V	500 to 1000	180 Wh/kg	Drives, high current
LiPo	3.7 V	300 to 500	150 Wh/kg	Mobile devices
$LiFePO_4$	3.2 V	1000 to 5000	100 Wh/kg	Drives, high current
NiCd	1.2 V	600 to 1500	50 Wh/kg	General purpose, high current
NiMH	1.2 V	300 to 600	75 Wh/kg	General purpose
Lead-acid	2.0 V	300 to 500	35 Wh/kg	Emergency back-up supplies, starter batteries
RAM	1.5 V	50 to 500	50 Wh/kg	General purpose, low current

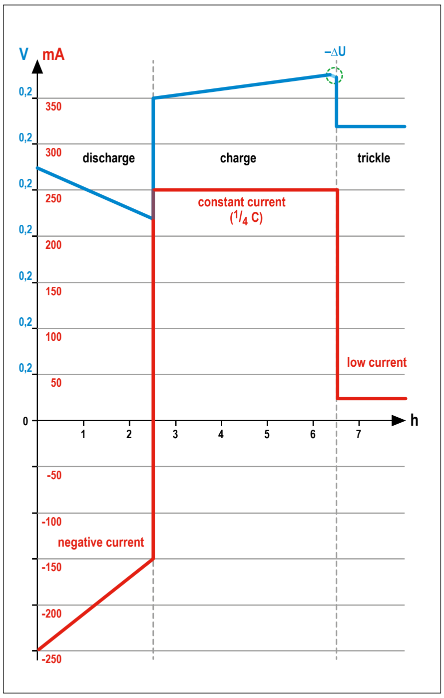

Figure 9. Idealized curves for delta-V charging of a NiCd cell at 0.25 C. In order to reduce the memory effect the charging cycle begins with a discharge phase.

NiCd batteries: Simple NiCd chargers have been around for a long time: these simply charge the battery at a low constant current. It is common to find 1-Ah AA-size cells or similar in devices such as electric pepper grinders or handheld vacuum cleaners with a plug-in charger that initially charges at 0.1 *C*, falling back to a continuous charge at perhaps 50 mA. The NiCd chemistry can withstand this overcharging for quite a while, but eventually the cells will be damaged. For this reason, and to improve charging time, a technique known as 'delta-V' charging is used. This technique exploits the fact that a fully-charged battery will turn excess charging power into heat, and the increase in cell temperature leads to a small drop in the cell voltage: see **Figure 9**. The charging circuit thus simply has to detect the point at which the voltage starts to drop.
This type of charger is also capable of fast charging. A charge current of 0.5 *C* or higher can easily be used with cells that are designed to support it. Note also that NiCd cells do not like to be deeply discharged, and should be recharged when their terminal voltage reaches 0.9 V.
One particular aspect of NiCd chemistry is the **memory effect** mentioned above. If a NiCd cell is repeatedly partially discharged and then fully recharged it starts to notice that only a fraction of its capacity is being used and then its maximum usable capacity starts to fall: this is a result of the formation of cadmium microcrystals. It is possible to reverse this process by repeatedly discharging the cell to below 0.9 V. The better microprocessor-controlled chargers take this into account and start each charging cycle by completely discharging the cell.

NiMH batteries: Most of what we said above for NiCd batteries goes equally well for their NiMH successors. NiMH batteries can also be charged using the delta-V method, although the voltage drop is less significant, especially at lower charging currents. For this reason higher charge currents are used, and this works well because the internal resistance of the NiMH battery is lower and hence it can be charged more quickly: up to 1 *C* is possible. In the interests of safety fast chargers also contain temperature monitors in case the fall in voltage is not detected. Since NiMH batteries do not suffer from the memory effect, there is no need to start each charge cycle with a discharge phase. NiMH-compatible chargers therefore allow the user to choose whether the discharge phase should be included in the cycle. Also, with the newer NiMH cells that have a very low self-discharge, it is possible to dispense completely with trickle charging at the end of the cycle. Looking at Figure 9, only the part of the cycle between the two vertical dotted lines is required. **Figure 10** shows a universal NiCd and NiMH quick charger for four AAA or AA cells.

Lithium batteries: All three types of lithium battery are usually charged using a CC/CV technique like the one used with lead-acid batteries. In comparison to Figure 8 the only thing that changes is the voltage scale; and because of the low self-discharge of less than 1 % per month no trickle charge is necessary at the end of the cycle. Depending on the application of the cells the charging current can be much higher than is possible with other chemistries. In the example of the Tesla cars, we have the ability to charge to 80 % of capacity in 20 minutes, which corresponds to a charging current of 2.7 *C*. On the other hand the final constant-voltage phase lasts relatively longer, and it takes another 40 minutes or more to reach full charge. The USB charger shown in **Figure 11** charges its 18650-size 2.4 Ah battery at a leisurely 0.5 A, or 0.2 *C*. But be careful: if a battery is deeply discharged it must be recharged initially at 0.5 C or less until its voltage reaches a certain threshold.
The memory effect and other such undesirable properties do not affect lithium cells. The only thing to watch is that you do not discharge them too deeply. $LiCoO_2$ cells in 18650 size (18 mm in diameter and 65 mm in length) are available in versions with integrated electronics (as shown in **Figure 12**) that protect against deep discharge, overcharging, and short-circuit. This is an ideal solution for flashlights and the like, at the cost of a slightly increased effective internal resistance. The main difference between the different types of lithium cell lies in the voltage characteristics: **Table 2** summarizes the relevant values. If the man-

Table 2. Voltage characteristics of different types of lithium batteries.

Type	Nominal voltage	Charge termination	0.5 C threshold	Discharge termination	Deep discharge
$LiCoO_2$	3.6 V	>4.1 V	2.9 V	3.0 V	<2.5 V
LiPo	3.7 V	>4.2 V	3.0 V	3.2 V	<2.6 V
$LiFePO_4$	3.2 V	>3.7 V	2.4 V	2.5 V	<2.0 V

ufacturer does not specify otherwise, you will not go far wrong if you assume that the maximum charging current is 0.5 *C* and that the constant voltage phase should be terminated when the current falls to 0.05 *C*. Terminating this phase is recommended as the cells should not be subjected to the maximum voltage for an extended period. So charging lithium cells is not too troublesome, as long as you can charge them individually. If you have several cells wired in series a charge balancing circuit is essential to ensure that the cell that has the lowest capacity is not overcharged and hence damaged. The LiPo pack in Figure 4 has a special connector for this purpose, and the homemade $LiFePO_4$ pack in Figure 6 includes a particularly high power charge balancer that is capable of diverting large currents away from the individual cells. The technology and circuitry in charge balancers can be complicated, and a full treatment would occupy an article in itself.

Figure 10. Low-cost charger for 18650-size LiCoO2 cells with a USB connection and OLED display.

Figure 11. Intelligent quick-charger for four AA- or AAA-size NiCd or NiMH cells working at up to 0.8C. The device can even detect defective batteries. A press of the blue button discharges the cells before the charging cycle starts

RAM batteries: Chargers for these batteries use a special technique. They start by charging at a relatively low constant current (in the region of 0.1 *C*). This current is interrupted periodically for a few milliseconds and during this time the no-load terminal voltage of the cell is measured. If this voltage exceeds 1.73 V then charging stops and is not resumed until the voltage falls below 1.69 V. It is very important that the cells are not overcharged and in particular that they are not subjected to deep discharge: the threshold for this is as high as 1.42 V per cell. For this reason RAM batteries are not likely to gain wide acceptance unless they can be made with built-in protection circuitry.

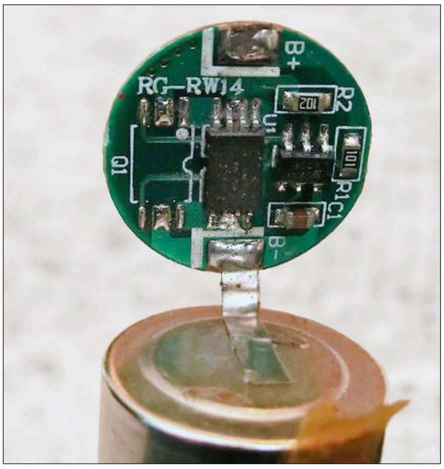

Figure 12. A circuit built into an 18650-size LiCoO2 cell protects it against deep discharge and overcharging.

General remarks

Since the advent of microcontrollers it has been easy to implement complex charging strategies. The information given in this article is in principle enough to let you develop your own charging circuit for any of the cell types we have looked at. One indispensable feature of a homebrew charging device is a cutoff timer. When all else fails and, for example because of a defective cell, the circuit does not correctly detect the point at which it should stop charging, it is a good final line of defense to stop after a certain amount of time has elapsed. This is particularly the case for lithium cells. If charging continues the excess electrical energy will be turned into heat, and potentially cause a fire, especially in LiPo cells: perhaps you remember the unfortunate case of the rechargeable batteries in the Boeing 787 Dreamliner. An allowance of 25 % on top of the calculated charging time is a reasonable place to start. A deluxe charger for lead-acid batteries would include an ambient temperature sensor to allow a compensation of around 3 mV/K to be applied to the charge termination voltage.

For special-purpose battery packs do-it-yourself is invariably the way to go. For packs of standard AA-, AAA- or 18650-size cells there are ready-made commercial alternatives that are manufactured in large quantities that will work out cheaper.

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Web Link

[1] Lohner-Porsche: http://press.porsche.com/news/release.php?id=642

About the Author

Dr Thomas Scherer is an electronics engineer and qualified psychologist, and has been writing for *Elektor* for over 30 years. His specialties include analog electronics, microcontrollers and research in psychophysiology. He can almost always be found pottering around in his own spacious electronics lab, experimenting, assembling or soldering something or other.