Fundamentals of Qnovo Adaptive Charging in Lithium Ion Batteries

The purpose of this white paper is to provide a technically inclined reader insight into the challenges faced by lithium-ion batteries in mobile and consumer devices. The fundamentals of Qnovo's adaptive charging technology are introduced, and its benefits in enabling improved battery features such as very fast charging without battery degradation are discussed.

Introduction to key terms

A lithium-ion battery is a complex device that stores electrical energy in the form of an electrochemical reaction. A number of basic parameters and terms are often utilized to define this energy storage process:

"Battery capacity" is a measure of the battery's ability to hold electrical charge. The more charge it can hold, the longer the battery life and the longer a consumer can use their mobile device. Battery capacity is typically measured in Amp-hours (Ah) or alternatively may be expressed in its ability to store electrical energy, measured as Watt-hours (Wh)

"Cycle life", also known as battery lifespan, is a measure of how many times a battery can be charged and discharged. It is the primary factor behind why consumers notice after a few months of use that their device can no longer last through the day. As the battery is charged and discharged, it loses its ability to hold charge. Battery capacity declines with usage; this loss is referred to as capacity fade. When battery capacity fades to 80% relative to its new capacity, it is considered depleted and should be replaced. Consumers often articulate their frustration with loss of battery capacity, but the culprit is usually rapid aging due to poor cycle life.

"Charge rate" or C-rate is a measure of charging speed. It is the amount of electrical current applied to the battery divided by the battery capacity. For example, a typical 5-Watt AC wall adapter supplies approximately 1 A into the battery. Assuming a 3 Ah cell, the C-rate is 1A/3Ah, or 0.33C. Faster charging equates to higher C-rates, typically 0.7C or greater. The higher the current, the faster it charges. As every consumer can attest to, batteries typically charge too slowly. This is due to the fact that charge rates using conventional charging methods are intentionally kept low to preserve cycle life.

To increase battery capacity AND increase cycle life AND shorten the charge times simultaneously without compromise, the charging process must be optimized for maximum efficiency. This is precisely what Qnovo's adaptive charging technology and software products do.

The basic structure and functionality of a lithium-ion battery

In its simplest structure, a rechargeable lithium-ion battery consists of two electrodes opposite each other with a gap that is filled with lithium ions suspended in a liquid or gel electrolyte solution. The positive electrode during charging is called the cathode, and the opposite electrode is called the anode. The physical transfer of lithium ions from one electrode to the other is the basis of storing electrical energy. The illustration in **Figure 1** shows the basic physical structure of a lithium-ion battery.

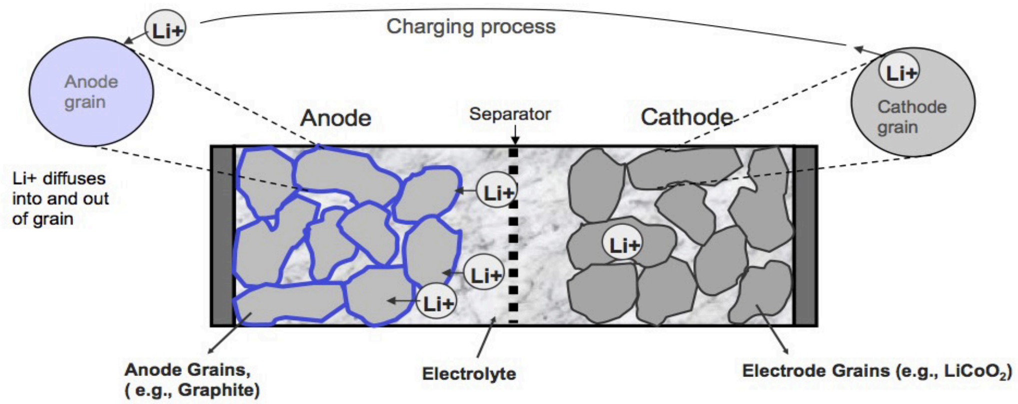

Figure 1: Illustration of the basic structure and operation of a lithium-ion battery. During charging, lithium ions move from the cathode to the anode, and are physically intercalated within the material grains of the anode. Graphite (carbon) is nearly universal for anodes. Cathode materials are usually made of a complex metal oxide, with Lithium Cobalt Oxide ($LiCoO_2$) commonly used for mobile and consumer devices.

The electrode layers are mechanically separated with a porous polymeric material called the “separator” – its role is to allow the ions to freely move yet prevent the two electrodes from electrically shorting and creating a safety hazard. **Figure 2** shows an electron microscope cross-section of the alternating layers of the battery: anode / separator / cathode.

Volumetric energy density is a key metric representing the evolution of lithium-ion batteries since the first commercial introduction by Sony in 1991. It is a measure of the stored energy in Watt-hours divided by the battery’s physical volume in liters, designated as Wh/l. This fundamental property drives the ability to increase stored energy without increasing the battery’s physical volume. Historically, it has increased at about 5% annually, primarily the result of denser packing of the materials described in **Figures 1** and **2**. A state-of-the-art polymer lithium-ion battery delivers an energy density near or greater than 600 Wh/l. A 3 Ah smartphone battery, equivalent to 11.4 Wh, occupies a tiny volume of 19 cc, which equates to slightly more volume than a tablespoon.

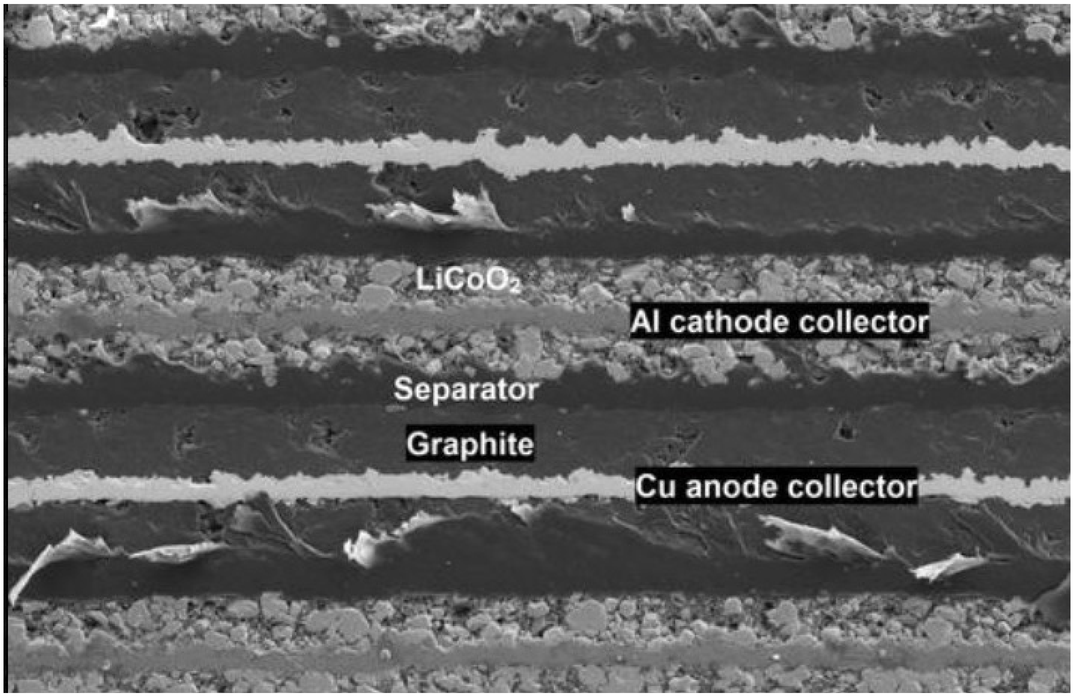

Figure 2: An electron microscope photograph of the alternating layers of a battery. The layers are typically 10 to 50 micrometers each. The granular nature of the layers is visible. The capacity of the battery is determined by the available material amount of anode and cathode. Battery manufacturers coat the electrode materials over large surface areas to increase the battery capacity to usable levels. Courtesy: *TechInsights*.

The role of charging in a lithium-ion battery

Charging is an integral part of the battery's practical utility to end-users, and also plays a significant role in the battery's performance. In particular, charging is a major culprit in the loss of capacity and cycle life.

Battery charging remains a relic of the early days of the lead-acid battery from the 19th century. It uses a simple approach named CCCV, an acronym for "constant-current, constant-voltage," as illustrated in **Figure 3**. Charging begins by applying a constant DC current to the battery, what is called the "CC phase." During this phase, the battery's voltage at its terminals rises until it hits a maximum allowed voltage – primarily for safety reasons. At this point, the charging electronics switch to applying a constant voltage to the battery's terminals. The charging current gradually decays until the battery is fully charged, at which point the charging current becomes negligible.

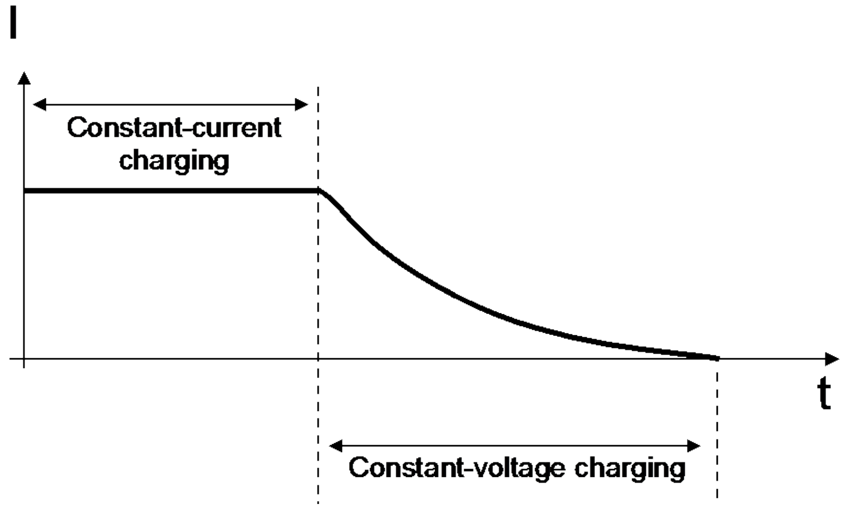

Figure 3: CCCV charging consists of a sequence of two steps: (i) *constant current*, during which the battery voltage rises, and (ii) *constant voltage,* after the battery reaches a predetermined maximum voltage.

CCCV charging does not take into consideration any of the degradation mechanisms that are inherent to the battery's chemistry – as a result, it amplifies any minutely present damage within the battery and accelerates capacity loss (**Figure 4**). It also lacks any means to compensate for varying operating conditions such as temperature or age. In a simple analogy, it is akin to unleashing a barrage of cars onto a highway with no consideration for traffic management; the result is a traffic nightmare with an elevated risk for accidents.

One such damage mechanism is lithium metal plating. The anode has a limited acceptance rate of lithium ions during charging. Uncontrolled CCCV charging, especially during fast charging, results in excessive accumulation of lithium ions at the boundary of the anode. The result is the formation of unsafe lithium metal: lithium ions will favor bonding together instead of making their way inside the anode material.

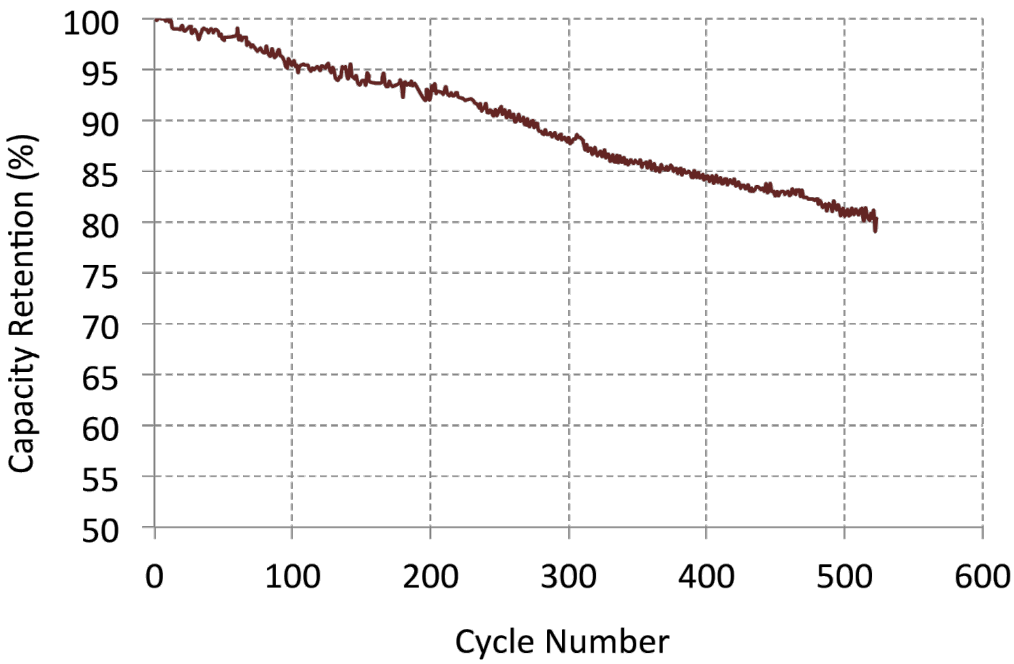

Figure 4: A lithium-ion battery loses some of its capacity through use. When it reaches 80% of its original capacity as a new battery, it is deemed depleted and unusable. CCCV charging is responsible for greatly accelerating this capacity loss. For a consumer device that is charged daily, 500 cycles corresponds to only one and half year of operation, typical of most modern smartphones.

There are several other degradation mechanisms that may take place during a battery's operation. In addition to lithium plating, a thin protective layer on the surface of the anode, called the SEI layer, may grow uncontrollably thus consuming precious lithium ions. The grains of the electrodes, especially the anode, may also pulverize under the repeated mechanical stress of intercalated lithium ions. The integrity of the electrolyte – the solution that facilitates the physical transport of the ions – is also another factor to take into account. By all measures, historical charging methodologies including CCCV failed to consider these important degradation mechanisms. The result has been a premature loss of battery capacity, worsening cycle life performance and unnecessary compromises by the battery manufacturers.

And to make matters worse, the demand for higher energy density and faster charging are accentuating these problems – as witnessed by the constant battery complaints from users of mobile devices.

You can't fix what you can't measure

Qnovo's adaptive charging technology is predicated on real-time *in situ* diagnosis of the degradation mechanisms that occur within the battery as a result of its operation and due to inherent manufacturing variations. Qnovo leverages the existing large body of scientific knowledge related to battery degradation and cleverly adapts it into compact computational algorithms that operate in real-time on commonly available processors within modern consumer devices.

One critical diagnostic measurement that Qnovo derives with each charging cycle for every battery is an effective diffusion time of the lithium ions as they make their journey from the cathode to the anode. This diffusion time governs the effectiveness of the battery materials and design in the storage reaction. Naturally, one can readily gather that this measurement depends on several factors including the manufacturing process, temperature, battery age and health.

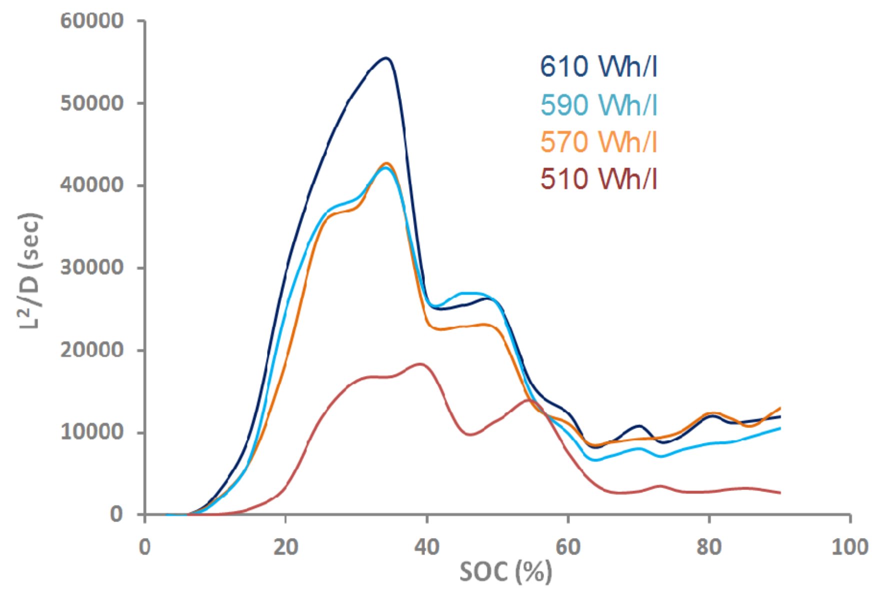

Figure 5: The diffusion time of lithium ions is one of several key diagnostic measures Qnovo's algorithms perform in real- time during charging. It depends on several design and operating factors, including energy density. Higher values of diffusion time strongly correlate with increased battery degradation.

Electrochemical Impedance Spectroscopy (EIS) is a diagnostic tool widely used by chemists in battery laboratories around the world. It provides valuable insight into a continuum of chemical processes within the battery and has been a workhorse in battery development. EIS measurement equipment is expensive and bulky with a test cycle typically taking several hours, thus making it impractical for use in consumer devices. Qnovo's algorithms are able to reconstruct through appropriate signal processing techniques sufficient portions of the EIS spectrum to gain equally valuable insight into the chemical processes, but perform such functions in real-time and *in situ* within a consumer device. **Figure 6** depicts a reconstructed EIS graph of a battery in a mobile smartphone using Qnovo's algorithms.

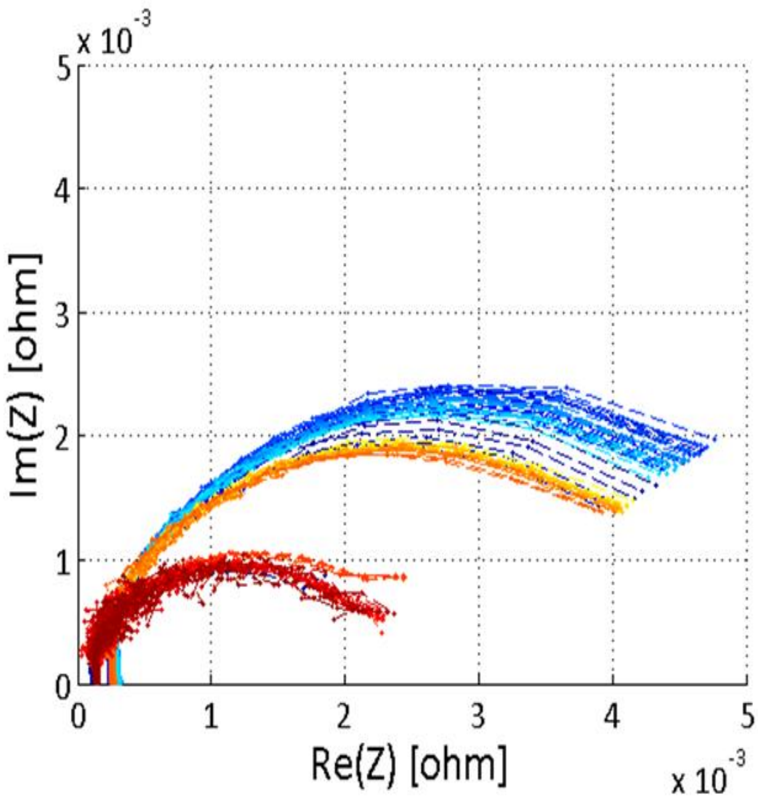

Figure 6: Qnovo algorithms reconstruct *in situ* the EIS graph of a mobile smartphone battery. The semi-circular curves display the real and imaginary components of the battery impedance over a range of frequencies, in this particular case, spanning from 10 Hz to 10 kHz, representing a number of processes including ion kinetics and growth of the SEI layer.

Such diagnostic measurements performed *in situ* provide real-time data into the health of the battery and the chemical processes that govern the battery's behavior. Naturally, these data vary with operating conditions, e.g., temperature and usage, as well as design and manufacturing origin. We routinely observe stark differences and signatures that we uniquely attribute to particular battery manufacturers and designs. Qnovo has accumulated a large set of test data covering lithium-ion batteries from major battery manufacturers including LG Chem, Sony Energy, Samsung SDI, ATL and others. This set of diagnostic tools enables Qnovo's algorithms to distinguish unique characteristics of batteries and shift the burden of correcting inherent battery problems from expensive manufacturing processes to much less costly readily-available computational power.

The need for adaptive systems: Closing the feedback loop

In principle, an optimal charging profile (inherently different from CCCV) may be obtained by solving the set of non-linear equations that describe the chemical processes within the battery. However, a numerical solution is highly impractical. First, it completely ignores the uniqueness of each battery. There is sufficient variability in the manufacturing of batteries, their material properties and operating conditions that it is essential to have an adaptive system to monitor these differences and close the loop – in other words, there is not a universal static mathematical solution. Secondly, solving these equations is computationally intensive (taking hours on a high-end computer) and cannot be practically implemented in a consumer device. Finally, owing to the exponential nature of the chemical processes, small deviations from the optimal charging point are rapidly amplified and become detrimental. This places unique requirements on the nature of the adaptive algorithms and corresponding feedback systems; and yet such systems need also to perform with as little power consumption as possible.

Figure 7 illustrates Qnovo's adaptive charging process, where the feedback loop is closed by dynamically modulating the charging current. Traditional charging methodologies including CCCV rely on applying static DC currents. In contrast, Qnovo's algorithms use a broader spectrum of frequencies both to excite the battery response and to modify the charging current. In particular, Qnovo's most advanced Adaptive Pulse Modulation™ algorithms use a sequence of short charging pulses separated by measurement periods, and then adaptively modulate these charging pulses in relation to the received diagnostic results. It is very important to distinguish this approach from past "pulse charging" approaches. Pulsing is not the key characteristic of Qnovo's charging; it is rather the closed loop behavior and modulation of the charging signal that make our algorithms effective. Pulsing is only one practical way to modulate the charging signal.

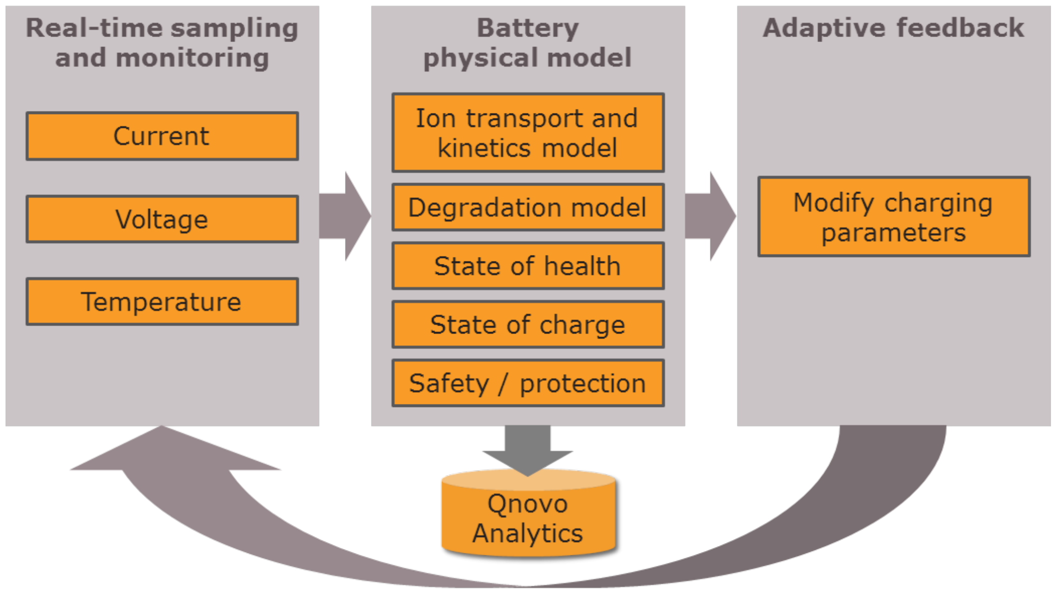

Figure 7: An illustration of the basic elements of Qnovo's algorithms. The diagnostics require sampling the current, voltage and temperature of the battery. No modification of the battery is required. A model of the battery performs the requisite analysis of the diagnostics data; modulating the amplitude and timing of the pulses in the charging signal closes the feedback loop.

Benefits of using adaptive charging

The improvement in battery performance from adaptive charging can be quite significant. **Figure 8** shows an example of a typical polymer lithium-ion battery used in a mobile smartphone. The cell is rated at a capacity of 2.5 Ah with a state-of-the-art energy density of 560 Wh/l manufactured by one of the leading battery suppliers. To deliver the minimum necessary cycle life of 500 cycles with traditional CCCV charging, the battery can only be charged at a maximum charge rate of 0.5C – corresponding to a maximum charging current of 1.25 A, and a total charge time of 3 to 4 hours.

The capacity fade curve in **Figure 8** highlights the challenge of fast charging. Increasing the charging current by 3X to 3.75 A (also known as

1.5C) using conventional CCCV creates so much damage within the battery that the cycle life degrades from the nominal 500 cycles at low charge rate to a measly 100 cycles – in other words, this battery is rendered useless and unsafe within months. Replacing the CCCV charging protocol with Qnovo's adaptive charging algorithms has a dramatic effect on the battery performance. Cycle life climbs to 800 cycles, capacity loss is greatly reduced and the battery charges 3X faster. Qnovo adaptive charging gives this battery exceptional performance combining high energy density, long battery life, long battery lifespan (cycle life), and naturally, very fast charging – all at the same time. This is what we mean by no compromise charging.

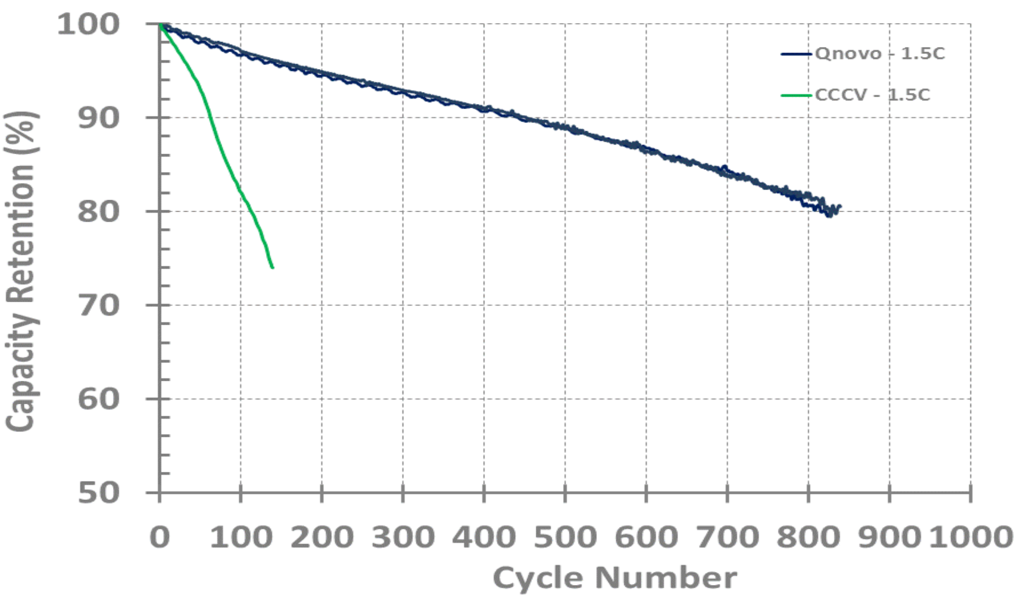

Figure 8: The battery's capacity fade curve illustrating its lifetime ability to charge and discharge is greatly impacted by the charge rate and type of charging algorithms. CCCV charging at a fast charge rate of 1.5C results in such great damage to the cell that its cycle life is reduced to 100 cycles, rendering it useless for consumers. In contrast, charging the cell under otherwise identical conditions but using Qnovo's adaptive charging algorithms at 1.5C extends the battery cycle life to 800 cycles.

A serious adverse condition of fast charging that is seldom discussed in the media is battery swelling. A polymer lithium-ion battery grows in thickness – swells – with use and time. The extent of this growth depends on several factors, one of which is speed of charge. Device manufacturers typically allow for additional space to accommodate battery thickness growth. But in an age where consumers are favoring thin and sleek devices with embedded batteries (not just smartphones but thin tablets and smart watches), battery swelling is now playing an important and limiting factor in design. Now in addition to capacity, cycle life and charge rate considerations, a design engineer must take into account cell swelling. **Figure 9** compares battery swelling as a percentage of its initial thickness between conventional CCCV and Qnovo's adaptive charging.

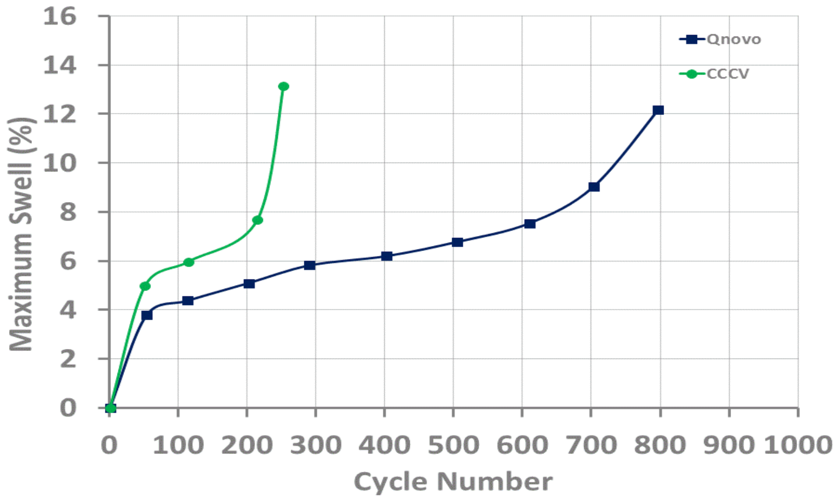

Figure 9: A polymer lithium-ion battery swells with use. The swelling is a function of cycles as well as speed of charging. Device manufacturers allow for swelling in their designs, typically up to 10% of the battery's original thickness. Fast charging using CCCV results in excessive swelling such that the battery exceeds its maximum thickness very rapidly. Qnovo's adaptive charging is very effective in controlling battery swelling. The battery in this particular case is rated at 2.4 Ah and was charged at a rate of 1C (equivalent to 2.4 A).

Safety first

Battery safety is of paramount importance. While every lithium-ion battery comes with associated protection circuitry to prevent unsafe conditions such as over-voltage and over-current, our philosophy is that this protection should activate only as a last resort. Intelligent algorithms and software should complement such protection circuitry, and should be active at all times during the operation of the battery, closely monitor its health and make the appropriate decisions to ensure that unsafe conditions are always avoided.

Qnovo's algorithms incorporate several features designed to raise the safety level of lithium-ion batteries. For example, our predictive analytics tools can project forward the state-of-health of the battery and enable an estimation of the progression of the inherent degradation mechanisms. Should our algorithms identify a cell that may be suspect, precautionary measures are taken well in advance to avoid the possible occurrence of a catastrophic failure.

Summary

Qnovo adaptive charging adopts an innovative and unique approach to battery charging, utilizing software algorithms and existing computational power in mobile devices to significantly improve the performance of lithium-ion batteries. Qnovo technology does not require any modifications to the battery, and has been shown in extensive testing to work consistently across the spectrum of Li-ion suppliers and chemistries. Adaptive charging is complementary to ongoing battery chemistry and manufacturing improvements. Qnovo enables mobile device manufacturers to deliver a no-compromise mobile experience that alleviates the everyday pain consumers feel from battery performance limitations.