



Effects of the Fast Charging on Lithium-Ion Battery: A Review

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Abstract: Both academics and business have made a significant amount of effort in recent years to develop batteries with higher performance and lifetime. The preferred battery technology for smart phones, electric vehicles, and grid storage is lithium-ion batteries. The electrolyte density, design and implementation of the battery, storage technique, over and under charging, operating temperature, charging method, surroundings and operational condition, and the state of charge are the main elements that determine the battery's lifespan. It is well known that the high currents required to quicken the charging process impair energy efficiency and hasten capacity and power fading. The literature on the processes of deterioration brought on most frequently by charging at high currents is reviewed in the current work and discusses the rate limiting processes that prevent lithium-ion batteries from being charged quickly. These processes lead to degradation problems, which are made worse by quick charging. Lithium-ion battery deterioration is known to be ramped up by temperature and cycling rate.

Keywords - Lithium-ion battery, Fast charging, Electric vehicles, Degradation.

1. Introduction

Recent years have seen fast advancement in the creation of lithium-ion (Li-ion) battery-powered electric vehicles (EVs). This is due to attempts to reduce the impacts of climate change and local air pollution. Lithium-ion batteries have found widespread usage in the field of consumer electronics due to its high energy density, high power density, extended service life, and environmental friendliness when compared to other regularly used batteries. Nonetheless, the high capacity and enormous serial-parallel numbers of lithium-ion batteries for automobiles, together with issues with safety, durability, consistency, and cost, place restrictions on the widespread use of lithium-ion batteries in the vehicle [1]. Many times cited as the primary obstacles to the widespread adoption of EVs are range anxiety and lengthy charging durations compared to refueling of petrol cars [2]. Fast charging ability is becoming one of the important aspects that the battery and EV sectors are focusing on. High-rate charging has been demonstrated to hasten deterioration, which affects both the capacity and power capabilities of batteries. However, the heat produced during fast charging as a result of resistive heating is sometimes challenging to remove uniformly and effectively, resulting in accelerated deterioration and safety problems. Several manufacturers have focused on the difficulties with quick charging. The CHAdeMO quick charge standard, developed in collaboration by Toyota, Nissan, and Mitsubishi, is swift enough to charge a Nissan LEAF to 80% State-of-Charge (SOC) in around 30 minutes [3]. Another standard is the Combined Charging System (CCS), which is based on open and global standards for electric cars. The CCS inlet incorporated the DC charging option (up to 200 kW) into their present AC Charging system. Future projections for the DC charging option call for 300 kW [4]. Tesla is also developing its own Supercharger Network, which can provide up to 120 kW of charging power for its Model S and X all-electric cars [5]. The suitability of the active materials in lithium-ion batteries, pack design and thermal management, charging algorithm [6], and power electronics converters in the charger are some of the variables that affect a lithium-ion battery's capacity to execute rapid charging.

Continual charging power is often rated lower than the charger's power rating and is influenced by the EV's specs as well as the surrounding environment. According to the Nissan LEAF Owner's Manual [3], charging an electric vehicle to 80 percent State-of-Charge (SOC) with a 50-kW charger can take anywhere between 30 and over 90 minutes, depending on the ambient temperature. In particular, charging speeds are significantly reduced at low ambient temperatures. Additionally, because to safety restrictions, rapid charging rates are often only possible up to roughly 80 percent SOC level [7]. The current must be gradually reduced at high SOC's in order to prevent going above the maximum cell voltage limitations, which necessitates substantially longer charging periods. The Battery Management System (BMS) on the car and the charger both have a limit on the maximum charging power.

The discussion of key factors that affects Li-ion battery fast charging are arranged in a different section. In Section 2, describes Thermal degradation phenomena that restrict fast charging capability in Li-ion batteries. In a section 3, lithium plating phenomena has been discussed and Mechanical effects on lithium-ion batteries are explained in section 4. Finally, section V concludes the presented work.

2. Thermal Effect

Temperature dependency may be seen in many of the deterioration processes that occur in Li-ion batteries. For large format cells, these inhomogeneities are exacerbated. Figure 1 illustrates that for cylindrical cells in particular, the temperature inside the battery core is substantially greater than the surface [8]. Additionally, because the aluminium current collector on the cathode side has a larger ohmic resistance than the copper current collector on the anode side, the temperature near the positive tab is frequently higher than the temperature near the negative tab.

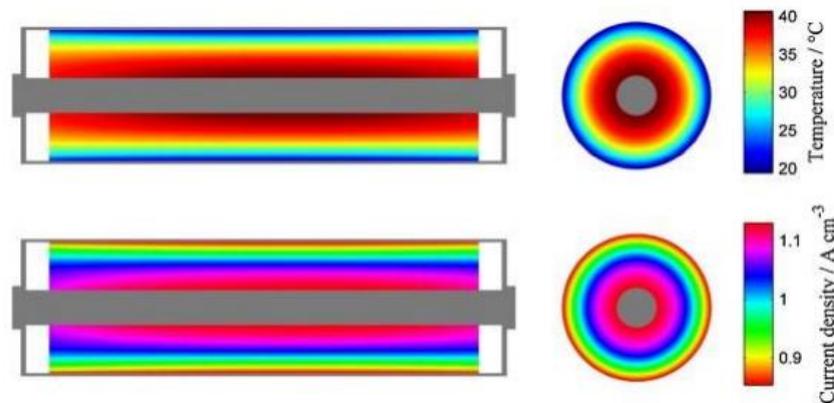


Figure 1: Distribution of temperature and current density during SoC-neutral pulse cycling in a cylindrical 4.4 Ah cell with a 70 A pulse amplitude. [9]

In Li-ion batteries, heat can flow from certain places easier than from others: for instance, the low through-plane conductivity of battery materials such polymer separators results in increased heat build-up in the core compared to the areas closer to the surface. Additionally, the rates of heat production and current densities vary widely around the globe. Due to the unevenly distributed current during cycling, the rate of heat generation in the various locations is not constant. The position of tabs and a temperature gradient can both contribute to the nonuniformity of current density [9]. High current density close to the tabs might cause local overcharge or over discharge, which could cause localized failure [10]. Varied local rates of side reactions and hence different local degradation rates might result from the inhomogeneities non the temperature and current distribution [10]. The temperature impact has been studied in the past using Arrhenius equations [11] or empirical equations fitted to experimental data [12]. The anode's SEI layer expands more quickly and becomes porous and unstable at high temperatures [13]. Low temperatures, on the other hand, result in slower intercalation and diffusion with a potential for lithium plating and subsequent lithium dendritic development [10]. The cathode may experience metal dissolution, phase transitions, binder degradation, and CEI development as a result of cycling-induced temperature rises [14,15]. In general, high temperatures speed up the majority of deterioration processes. A decrease in temperature can delay the pace of deterioration, but low temperatures unfavourably impede the diffusion of active species and alter the chemistry of the reaction, which can speed up degradation if metallic lithium begins to build on the anode. As a result of greater transport constraints and slower kinetics, operating at low temperatures also results in reduced energy efficiency [16] and more heat production.

Uneven heat generation occurs at more than only the cellular level. The architecture of the pack and the design of the thermal management system are two design considerations that have a significant impact on the temperature changes within a pack. Furthermore, investigation on heat generation in battery packs with parallel-connected cell arrangements employed a linked electrochemical-thermal model [17]. It has been demonstrated that finite interconnect resistances cause uneven connection overpotentials, which, in turn, causes load imbalances and non-homogeneous heat production between cells. The increased heat produced by rebalancing between pulses during pulse loading made these effects worse. Due to the uneven rise in cell resistances with time, it is also predicted that differing degradation behaviours among individual cells would have a significant impact on the homogeneity of heat generation in an aged pack. Temperature gradients that occur might in turn exacerbate the variations in cellular ageing behaviours. Under the majority of cycle circumstances, one of the primary degradation processes in Li-ion cells is the SEI growth at the anode/electrolyte interface. The power is reduced by the passive surface layer's increased on the cell impedance. Because the SEI can't recover the lithium it uses, capacity fading occurs. The electrochemical reduction of the electrolyte that produces the complex combination of SEI with lithium species such LiF, Li₂CO₃, and (CH₂OCO₂Li)₂ is temperature dependent [18]. The SEI layer that forms initially may serve a protective purpose, but with repeated cycling, it becomes unstable and expands to obstruct electrode pores or even pierce the separator, leading to safety concerns as well as an impedance rise from the reduction in active surface area. The integrity of the protective thin layer has been observed to be disrupted at high temperatures (60 °C or higher) by the dissolution and breakdown of SEI species, such as Li₂CO₃ for example and this results in the formation of separate islands [19]. In addition to producing the SEI on the graphite anode, the carbonate-based electrolyte can be thermally decomposed to produce a variety of additional by products, including as carbon monoxide, carbon dioxide, hydrogen, ethylene, alkylfluorides, fluorophosphoric acids, etc. Li/chromium-based-oxide (Li/CBO) cells cycled at 55°C recovered lithium methyl carbonate from the separators [20]. LiPF₆ dissociates into PF₅ at 60 °C, dissolving the protecting SEI and exposing a brand-new graphite surface [21]. LiPF₆ is not stable at this temperature. Nuclear magnetic resonance (NMR) spectra of 1.0 M LiPF₆ in EC/DMC/diethyl carbonate (DEC) [22] comparison revealed that the thermally induced breakdown processes became prominent at 85 °C. The mechanical characteristics of the anode and the cathode are additionally compromised by the production of gaseous by-products during SEI formation and electrolyte breakdown.

Electrode delamination and particle cracking are also harmful to a battery after extended exposure to high temperatures when parasitic reaction by products build up. After being stored in electrolyte at 60°C for three weeks and during cycling, a polyvinylidene fluoride (PVDF)-bound LiNi_{0.5}Mn_{1.5}O₄ cathode from the Al current collector showed signs of delamination [23]. Fast charging/discharging, temperature variations, and volume changes in the electrode material cause stress that finally leads to cracking

and delamination when the binders are unable to hold the electrode fragments together [24]. According to research, the carbon additives in the cathode are electrochemically active toward PF_6 intercalation, which results in structural alterations in the cathode. At 45°C compared to 25°C , the effects are more pronounced [25]. Higher temperatures are primarily responsible for the acceleration of other structural instability-causing processes, such as the interaction between electrolyte oxidation products and corrosion from hydrofluoric acid (HF). Thermal runaway may happen in severe circumstances when the temperature increases over the safety threshold. When an exothermic reaction rate and the associated temperature rise encounter unchecked positive feedback, the phenomenon is known as thermal runaway. Anode/electrolyte and cathode/electrolyte interactions, electrolyte breakdown, and reactivity with the binder are among the series of events that occur during thermal runaway [26]. Exothermic disintegration of metastable components like $(\text{CH}_2\text{OCO}_2\text{Li})_2$ is linked to the collapse of the SEI layer as a result of overheating, overcharging, or physical abuse [27]. This is followed by further exothermic interactions between the anode and the electrolyte. Although certain separators are made to retain structural integrity and avoid a short circuit, most polymer separators dissolve at temperatures exceeding 130°C . Tri layer PP-PE-PP (polypropylene, polyethylene, and polypropylene) separators, as an illustration, can be designed to demonstrate a shut-down procedure when temperature exceeds a threshold. The separator loses its porosity and ion-conductive properties when the PE layer melts, which prevents the cell's electrochemical process from continuing. Due to their higher melting point, the PP layers keep their mechanical characteristics at the same time, preventing short circuits and separator shrinking [28]. Alternately, a technique for causing thermal shut-down by adding an additional material layer between the cathode and the current collector [29]. The substance had strong electrical conductivity at moderate temperatures and was composed of spiky nickel nanoparticles covered with graphene and embedded in a polymer matrix. Its electrical conductivity plummeted by seven to eight orders of magnitude in a second at high temperatures (70°C in the research, but adjustable based on the choice of polymer matrix and nickel-to-polymer ratio), essentially shutting down the cell and preventing thermal runaway. The cell is internally short-circuited, which causes the cathode to fail if thermal runaway is not properly prevented before the melting of the separator takes place. When a thermal runaway occurs, electrolyte dissolution occurs severely between 250 and 350°C with a fast release of gaseous species, increasing cell pressure until it finally vents flammable vapour into the atmosphere [30].

3. Lithium plating

Lithium plating is a Faradaic side reaction in which lithium metal is formed on the surface of the negative electrode by Li^+ ions in the electrolyte rather than intercalating into it [14]. When the electrostatic potential of the negative electrode approaches or drops below that of a Li/Li^+ reference electrode during rapid charging, this process mostly takes place. Low temperatures and a lack of negative electrode material for the insertion of lithium are aggravating variables that slow down the competitive intercalation reaction. During cycling, lithium deposits progressively build up at the microscale. Capacity deterioration and an increase in impedance are the results of the electrolyte's side interaction with the plated lithium. The possibility of lithium plating causes ageing rates to rise at low temperatures, but ageing caused by SEI development speeds up with rising temperatures. Due to the greater conductivity of lithium metal compared to SEI, lithium plating largely affects the rate of capacity fading and has less of an impact on the rate of impedance increase [31].

Lithium metal first forms in droplets to reduce surface energy. SEI is formed when an electrolyte reaction occurs fast on the droplet surface. In what is variably referred to as "mossy" growth, "root growth" [32], or "base controlled growth" [33], the droplets are subjected to increased mechanical stress while more plating develops on the surfaces underneath the SEI. At this point, the SEI is broken and the lithium escapes. In addition to metallic lithium, mossy structure may also contain elements with higher atomic numbers, which were thought to be lithium salts. The mossy lithium develops new SEI forms, which prevents the homogeneous film production seen with less reactive metals like copper. Continuous moss growth causes the electrolyte concentration to fall below equilibrium, slowing down mossy development and encouraging dendritic or "tip growth" instead, which is growth that is perpendicular to the surface [32]. The dendrite will experience mechanical stress as it expands, which might break it or, in the worst situation, compress it and cause exponential growth. For good reason, dendritic development is known as the worst-case scenario; if a dendrite completely penetrates the separator to reach the positive electrode, an internal short-circuit is created, causing the cell to heat up quickly [34]. In the majority of cases, the ensuing heat generation instantly melts the dendrite and ends the short [35], but the temperature increase can also cause additional degradation processes such SEI development, electrolyte drying, and positive electrode disintegration. Fast charging at low temperatures is risky because to the possibility of short circuits, but even mossy growth reduces the porosity of the negative electrode and/or the quantity of electrolyte in the cell, which results in capacity fade and power fade. The potential to develop a blocking layer to the remaining active material exists because plated lithium frequently occurs at the electrode-separator junction. Graphite is substantially less reactive than metallic lithium, which encourages additional side reactions that lead to SEI development, gas production, and electrolyte dissolution [14].

4. Mechanical Effect

Another significant factor in fast charging-induced deterioration is mechanical pulverization, which has been repeatedly shown for a variety of electrode materials, including graphite [36], lithium nickel manganese cobalt oxide (NMC) [37], LCO [38], LMO [39], NCA [40], and Si [41]. mechanical pulverization depending on scale: electrode particle fractures, electrode particle isolation, conductive material and binders, separation of active material and current collector, and delamination between electrode sheets. The primary cause of these occurrences is the strain mismatch brought on by the gradient in lithium concentration, which is made worse by quick charging. In the course of fast charging, Li^+ ions rapidly intercalate into the anode and deintercalated from the cathode, creating a significant gradient in the lithium concentration as well as strain mismatches between various electrode particle regions and the creation of stress. When the energy release rate or stress intensity factor surpasses a specific threshold, cracks in the particles begin to spread [38]. There are always SEI/CEI fractures present along with this. Additionally, practically all types of electrode materials exhibit varying lattice strain along various orientations [39]. Primary particles are in direct touch with one another and are randomly orientated. Due to the inability to concordantly accommodate quick charging-induced strain between neighbouring primary particles, there can be isolation between electrode particles or between conductive material and binders. Additionally, fractures or separation might result from the strain mismatch between the electrode materials and current collector

[42]. Delamination may occur for cells without significant external limitations because larger C-rates cause more severe current inhomogeneity across electrode sheets [43]. Loss of active material (LAM), loss of lithium inventory (LLI), and impedance increase are the three categories into which the impacts of mechanical disintegration on cell performance may be classified. The first effect of cracks is poor electrical conductivity and occasionally complete separation. Second, the breaks expose more fresh surface, which interacts with the electrolyte [37]. The high temperature brought on by quick charging promotes these adverse responses [39]. The procedure causes the SEI layer to continue to expand, which raises resistance and resulting in LAM and LLI. Consuming the electrolyte can also make electrodes less wettable and make ion transport more difficult [37]. Higher rates cause more microcracks to develop, which worsen the differential between ion and electron transport since the ions can diffuse through the electrolyte injected into the fissures but the electrons can't. This causes severe SOC inhomogeneity and more cracking. Size dependency has been covered in several research on the mechanical implications of rapid charging. Smaller particles have smaller lithium gradients and energy release rates, which makes them more resistant to cracking [44]. Smaller particles, on the other hand, have greater specific surface areas, which causes an increase in SEI and impedance growth. Additionally, due to their lower packing density, tiny particles have a lower energy density [45]. As a result, secondary particles may contain main particles. However, because of the weak Van der Waals contacts, secondary particles' mechanical strengths are significantly lower than the inherent material strengths of original particles. Making bigger fundamental particles is another method to boost energy density [45]. Si nano-pillars [46] with a very small diameter (140 nm) do not break at any C-rate, but those with larger diameters (290 nm, 360 nm) fracture at the majority of C-rates. Particle design can benefit from the advice provided by models based on fracture mechanics in terms of stress intensity factor or energy release rate. In comparison to the free-standing circumstances in these models, the real boundary conditions are also more complex. It is still debatable whether greater C-rates inherently result in more secondary particle fractures. Operation at 1 C did not cause more cracks than 0.1 C for NMC333 [47]. This matches the outcomes for NMC532 at 0.5 C and 2 C [48]. However, with NMC622 operated at 1 to 10 C, cracks grew with C-rates, similar to NMC532 and NCA in references 135 and 143, respectively. This could be as a result of the alleged skin impact [48]. Simulations show that the hoop stress first rises with the current pace before falling at a maximum. Even when excessively high C-rates are used, the majority of Li⁺ ions may congregate at the particle surface while the lithium in other regions stays scattered. As a result, the hoop stress rapidly decreases in a thin region close to the surface, and the stress intensity factor is not significant.

Fast charging methods may be created using mechanical limitations. a procedure for exponential charge currents that uses the particle surface's hoop stress as a restriction [49]. Theoretically, this procedure might reduce the charge time with negligible cycle life loss. The model does not take into account any further degradation effects, and the validity of capacity retention through experimentation has not been done. a step-by-step charging technique that limits the amount of local, irreversible cell swelling and temperature increase that can occur [50]. Studies showed that, when compared to a 1 C constant current - constant voltage (CC-CV) protocol, the approach might reduce charge time and increase cycle life. Overall, there is still much to learn about mechanical deterioration in Li-ion batteries while they are being charged quickly.

5. Conclusion

There are no reliable methods to figure out when critical deterioration processes like mechanical operando cracking or lithium plating occur. Although ways to separate lithium stripping from other plateau-inducing events or to detect plating where no plateau is visible have not yet been disclosed, techniques for detecting lithium plating based on the distinctive voltage plateaus show promise for online application. The rapid charging capabilities of Li-ion batteries might be enhanced by a variety of other electrode materials, but additional research has to be done on these materials' stability, probable degradation processes, simplicity of fabrication, and cost. Despite being particularly vulnerable to lithium plating, graphite anodes are anticipated to continue to rule the Li-ion battery industry for the foreseeable future due to their low cost, widespread availability, and advanced technology.

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