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To What Extent Can Charging Strategies be Used to Aid the Development of Fast Charging in Electric Vehicles?

ME3 Literature Research Project

Department of Mechanical Engineering

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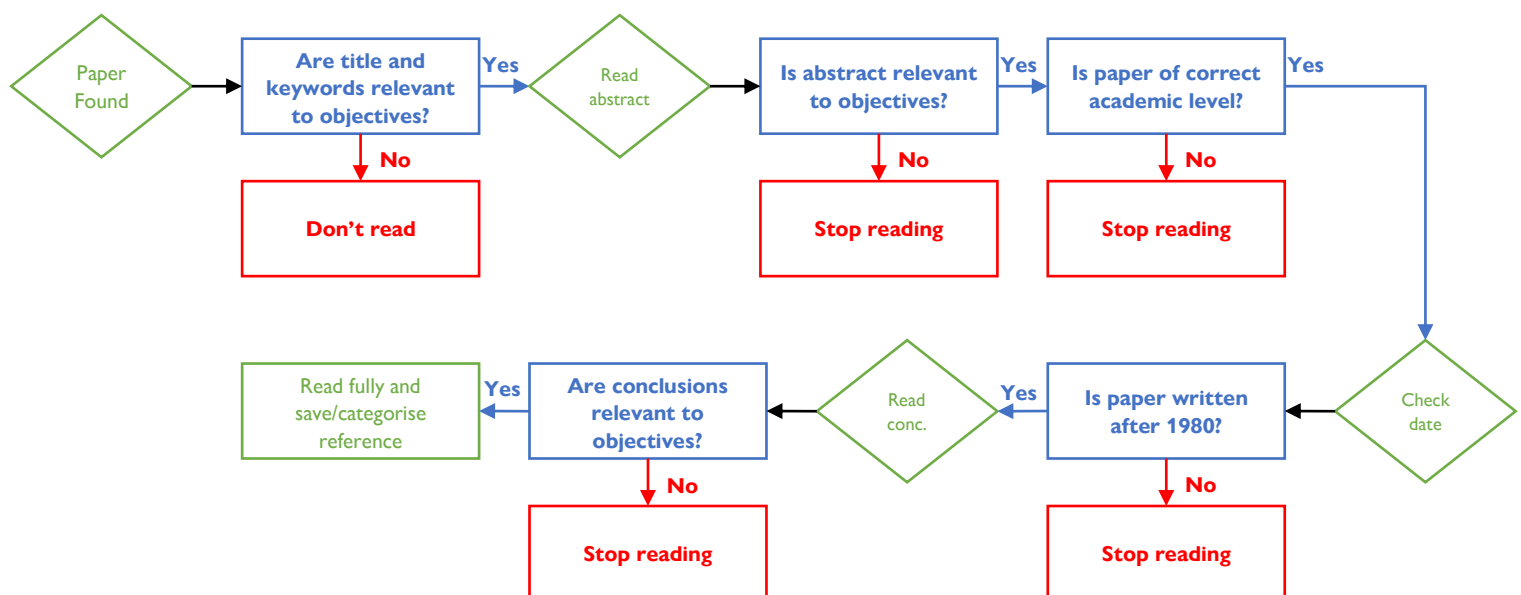Jake Reynolds

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Abstract

With new government legislation fading out conventionally powered vehicles, and an increasing percentage of electricity being produced by renewable means, there is a growing demand for electric vehicles, EVs, both for public and commercial use. Despite many technical advancements in the industry, one particular challenge remains; how can these vehicles be charged in time that will satisfy the ever faster pace of today's society? This literary review focuses on the current widespread technology of lithium-ion (Li^+) batteries and will outline the obstacles currently faced by fast charging, in particular compromising with battery degradation mechanisms. Charging strategies are introduced as a promising solution to the problem, and multiple profiles are reviewed, from the conventional static strategy CC-CV, to dynamic profiles such as MCC and MCC-CV. Optimisation algorithms are seen to drastically improve performance, and profiles capable of charging to 70% SOC in 30 minutes are found. Techniques such as pulse-charging and temperature-controlled strategies are also discussed, and it is found that improvements of over 16% can be see for charging time and battery degradation simultaneously. It is made clear that further development of a complete mathematical battery model and standardisation of the field will lead to more rapid developments, and that, when combined with other technologies, charging strategies can pave the way for the fast charging of EVs.

Reference selection

The following flow chart show the method used to select the major literature for this review.

Contents

1. Introduction

The interest in fast charging technologies has grown rapidly during the previous decade and continues to be an active area of research. With the European Union on track to reach its target of generating 20% of its energy from renewable sources by 2020 (1), owning an electric vehicle (EV) has ever increasing benefits for the environment. With the top end EVs already reaching the average mileage range for a petrol-powered car (2), it seems the predominant reason fewer people are investing in such a vehicle is due to the length of the recharging time. This review explores strategies used during charging as a method to decrease charge time.

Often in the automotive industry, technologies have been developed for the fast-paced competitive Formula-1 racing scene, before trickling down into the commercial world; from advancements in safety to novel energy storing flywheel systems (3). Unfortunately, this is simply not the case with EVs. Whilst the funding companies are using to back their Formula-E teams is growing, there is no need for them to develop battery technologies with a shorter charge time or a longer life-cycle. Charging can take place prior to race day and, should the battery pack lose a significant amount of capacity over time, it can relatively easily be replaced. This leaves the R&D up to car manufacturers and their scientists only, perhaps explaining why this conundrum is taking longer to solve.

As will be explained later, it is not possible to simply charge a battery at a very high voltage or current to decrease charge time, predominantly because of cell degradation. It is widely accepted that, for the same amount of cell degradation, the charging strategy or current profile that is applied to the battery can greatly affect the charging time (4,5). This review will explore both old and new charging strategies and assess the potential to combat the problem of fast charging.

Lithium-ion (Li^+) batteries are currently the most used power source in the EV industry (4) and, as such, this review will focus on this technology. The problems with fast charging could also be potentially solved using a change in cell materials or structure (6), however, it is worth exhausting the effects of relatively minor changes in charging strategies before deciding if a complete overhaul of existing physical technologies is necessary.

Manufacturers and consumers alike aspire to develop an EV that can fully charge in the time it would take to refill a petrol or diesel car's tank. Developing technologies capable of this could persuade significantly more people to invest in an EV and have drastic positive effect on the environment.

1.1. Objectives

The primary aim of this literature review on fast charging of EVs is to explore the ongoing research into charging strategies. More specific objectives chosen before research began are outlined below.

➢ To provide an outline of cell chemistry and key aspects of the charging process and cell degradation to aid the understanding of the effects of differing charging strategies.

➢ To present and evaluate a range of charging strategies, both new and old, and outline their effect at a cell level where possible.

➢ To compare the experimental results of literature and, where possible, identify the strategies best suited to aid development of fast charging using empirical data.

➢ To identify key next steps in research, development or implementation that must be taken to fully utilise any charging strategy solutions proposed. The overall research question to be answered is:

To what extent can charging strategies be used to achieve fast charging in Li^+ powered EVs?

2. Battery Fundamentals

The fundamentals of Li^+ cells and battery packs will be outlined in this section to provide a clear basis for the issues encountered when fast charging to be understood. Mathematical models of a cell will also be discussed, as it is vital to understand their limitations when used to test and optimise charging strategies.

This report focuses purely on Li^+ batteries with a carbon anode, due to their wide spread use in the automotive industry. Despite the large number of battery technologies available, with even more being developed regularly, Li^+ batteries possess a number of beneficial characteristics Abdel-Monem et al. (4) highlight these characterises, which are summarised below:

➢ Energy densities of between 200 and 500 watt-hours per litre (Wh/L) and power densities of up to 10 000 watts per litre (W/L) are some of the highest of developed battery

technologies. This high weight to power ration is the predominant reason for Li^+ battery's domination in the portable devices industry and allows EVs to remain relatively light.

➢ Life cycles of around 20 000 cycles. Despite the degradation mechanisms detailed in section 3, an Li^+ powered EV should, in theory, still maintain 80% of its capacity after 20 000 cycles of conventional charging and discharging.

➢ Both rapid and controlled discharge of power can be provided, making these batteries not only suitable for EVs, but allowing these cars to be some of the fastest accelerating road legal vehicles ever produced.

These advantages make that make it apparent that EV manufacturers will be relying on Li^+ technologies for years to come (7), and it is therefore worth continuing to improve the charging performance of these batteries, in parallel with developing entirely new technologies.

For EVs, and most other technical applications many of these cells are joined to form a battery or battery pack. The individual cells can be monitored using a battery management system (BMS). For thermal properties, a thermal management system (TMS) is used. For EVs especially, the battery can produce a vast amount of heat which, as will be seen later, can be detrimental to the battery itself. A cooling system is often used to control this, however cooling individual cells, which might heat at different rates is not feasible, and other approaches are necessary to combat battery degradation or temperature rise all together.

There are many models which incorporate many aspects of battery operation, however, a complete and fully accepted model does not exist (8). One aspect of the following discussion is the need a more complete mathematical model of the cell as a whole to accurately develop and test different charging strategies.

2.1. Charging Process and Modelling

The chemical nature of the charging process itself creates some of the challenges involved with fast charging. This section will outline the fundamentals of the charging process and focus on the intercalation of Li^+ into the anode for reasons that will become apparent. A schematic of the general charging process is provided for reference in Figure 1 (9: p.2954). Key terminology will also be introduced.
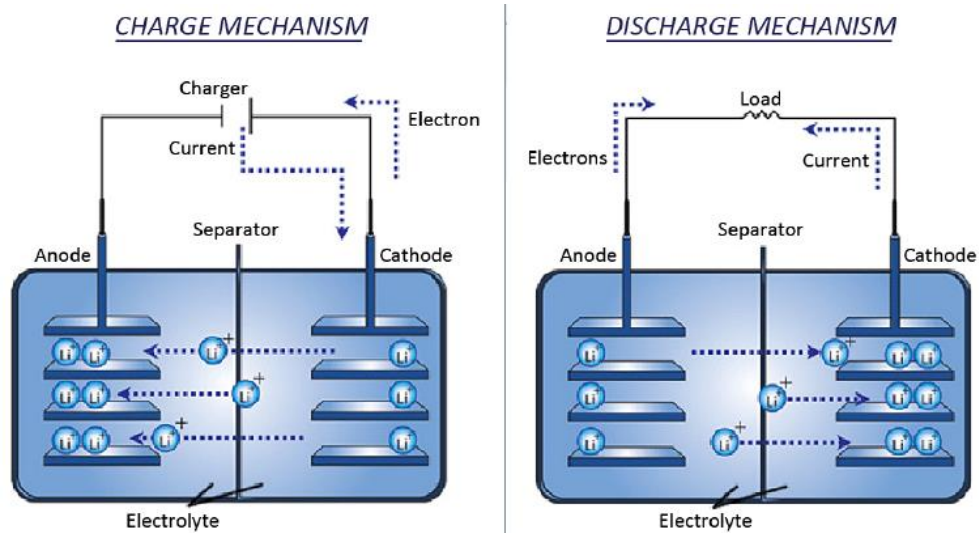

Figure 1 - A schematic of the general charring and discharging processes in Li+ batteries (9: p.2954)

As the battery is discharged, Li^+ move from the negative carbon anode, through the electrolyte, to the cathode. This movement is mirrored by electrons flowing through a device, the EV motor in this application, in the external circuit, in a process aptly named "rocking-chair" (10). During charging, a voltage is applied across the battery, driving the Li^+ back to the anode. Both charging and discharging are driven by the voltages at each electrode, and the electrochemistry of the cell must be carefully designed. The anode and cathode are layered structures, to allow the intercalation, or inclusion, of ions to occur. The electrolyte is formed of a Li^+ based compound, often lithium hexafluorophosphate, $LiPF_6$, dissolved in a mixture of organic carbonated. This mixture is selected such that it does not decompose at the voltages the Li^+ battery operates at, up to 4.2V (10).

This paper will focus on the effects of altering the properties of the external current or voltage applied to the battery during charging, also known as the charging strategy, on life cycle and charge speed. A static profile is defined as one which contains dynamic (4). The term C-rating is used to define standardise charging speeds, with 1C referring to a charging strategy that will fully charge the battery in 1 hour. Similarly, 2C charging would take 30 minutes, and 0.5C charging would take two

hours (11). The state of charge (SOC) refers to how far through the charging process a battery is at a given time. The SOC is defined in terms of the capacity of the battery, from full, 100% SOC, to empty, 0% SOC (12). Similarly, the state of health (SOH) is defined as the percentage of the total battery capacity that remains after a certain number of full charge-discharge cycles and is a useful measure of degradation. The battery is viewed to be at the end of its life cycle when it has reached 80% SOH (13).

The most important aspect of charging in this literary review is the intercalation process of Li$^+$ into the anode. This not only accelerates the degradation mechanisms outlined in section 3 but it is the rate determining step, or bottleneck, in the charging process. Li et al. (14) model this process using the diffusion equation shown below:

$$\frac{\partial c(r,t)}{\partial t} = D\left[\frac{\partial c^2(r,t)}{\partial r^2} + \frac{2}{r}\frac{\partial c(r,t)}{\partial r}\right] \tag{1}$$

$$-D\left.\frac{\partial c(r,t)}{\partial t}\right|_{r=R} = \frac{I}{nFA} \tag{2}$$

Here c(r, t) represents the concentration of Li$^+$ within the carbon anode, with respect to both position and time (r and t respectively). D is the intercalation diffusion coefficient which, as shown from Equation 2, depends on the current of the intercalating particle, I, the charge of the ion, n, (n=1 for Li$^+$), Faraday's constant, F, and the surface area of the particle, A.

In general, it can be seen from this model that an increase in Li$^+$ concentration and, more importantly, current, will result in a more rapid change in the concentration of Li$^+$ in the anode. In other words, it would result a faster charge (14). This corresponds with both intuition and experimental results and is reflected in the design of many charging strategies.

The charging strategies in section 4 are each designed to improve a particular aspect or aspects of the charging process, with the overall aim of improving either the battery life-cycle or charging speed. Whilst the methods used are vary drastically, the reasons behind specific choices can often be traced back to the fundamental cell chemistries discussed in this section.

3. Issues

Fast charging Li$^+$ batteries, in particular those in EVs, has a whole host of issues. Perhaps the most predominant issue is that faster charging can increase the rate at which degradation mechanisms occur, thereby decreasing the battery's lifespan and efficiency. As mentioned in section 1, any solution must compromise decreased charge time with battery degradation. There is little point fast charging a commercial EV in five minutes if it results in the lifespan of the car being drastically reduced. SEI formation and Li-Plating are the predominant degradation of concern to the automotive industry due to their susceptibility to temperature changes and C-rates. As such, these mechanisms along with other more general issues, will be discussed here.

3.1. Network

With many lines of research, a break-through in one area may not lead to advancements in consumer technologies without supporting developments in other parts of the field. This is especially true with fast charging EVs, with the primary supporting being a country's network infrastructure (15).

As described in section 4, the later stages of charging take the longest. For some EV's, if battery is at a very low SOC, the vehicle can be charged in 10 minutes to a range of over 60 miles. (16). This solution, however, would require, at the very minimum, charging station to always be within a 60 mile range from one another. This would be a large infrastructure development project and having to stop so regularly would be a huge annoyance for consumers. It a solution which can rapidly, and fully, charge EVs is still required.

Furthermore, strategies capable of charging an EV in one hour without causing significant life-cycle loss, have been available for many years, however, home charging still requires around eight hours due to the lack of power from the grid available. There is a need for grid updates should this charge time be reduced, and the research into presented here would predominantly be applied too commercial charging stations on road sides capable of delivering high powers.

Any further developments in fast charging EVs clearly needs to be coupled with an improvement in existing grid infrastructure.

3.2. Lithium Plating

Here, the fundamentals of lithium plating (Li-plating) and its dependencies will be outlined. This will provide a strong insight into the aims of certain charging strategies discussed in section 4.

Li-plating occurs predominantly during the charging process when Li⁺ is arriving at the anode. Under certain conditions, the ions cannot fully intercalate with the carbon, and forms Li metal at the surface. This results in the loss of capacity and therefore a reduction is life-cycle, due to the reduction in usable Li⁺. If the Li layer grows too large, it can lead to an internal short circuit, destroying the cell Lithium-plating occurs when there is a build-up of Li⁺ all waiting to intercalate at the surface of the anode, often brought on by high currents at a high SOC (17). A large negative potential at the surface will also cause the Li⁺ to form metallic lithium at the surface (5).

There is no greatest model to describe Li-plating, rather there are many (18). This makes battery modelling as a whole challenging and, as described later, has an impact on how charging strategies are optimised. Nevertheless, all models and experimental results for Li-plating agree that there is a strong temperature dependency too. The majority of accepted models, for example, as proposed by Doyle et al. (19), contain temperature dependent terms which are linked to an Arrhenius rate law given by Equation 3, below (20):

$$X_T = X \, exp\left[\frac{E_{a,x}}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \tag{3}$$

In general, X is any temperature dependant terms present in the model. Specifically, X_T is the value of X at temperature T and X is the value of that parameter at the reference temperature T_0 which fixed at a value depending on the study. Finally, $E_{a,X}$ is the activation energy for the term X.

The link to this Arrhenius law results in an inverse proportionality between the rate of Li-plating and temperature. This means that to avoid this degradation mechanism, batteries should be operated and charged at lower temperatures.

There is much ongoing research into how lithium plating can be prevented beyond changing battery operating temperature. Zheng et al. (21) added small concentrations of lithium compounds to the electrolyte and found that this can reduce the amount of Li forming at the anode. Despite this, it is widely accepted that selecting an optimum charging strategy based on the cell's chemistry, such as those described in section 4, can greatly reduce the effect of these degradation mechanisms (5,17).

3.3. SEI formation

The final degradation mechanism in Li⁺ batteries to be discussed here is the formation of the solid-electrolyte interphase (SEI). Discovered and aptly named by Peled in 1979 (22), the SEI most often referred to as a degradation mechanism however, without it, the battery would not function at all (23). As with Li-Plating, its fundamentals and dependencies will be presented here to provide a sound basis for the following section.

Under certain conditions, Li⁺ do not intercalate with the anode. Instead, the ions directly react with the organic compounds present within the electrolyte to form a solid at the edge of the electrode, the SEI (24). Figure 2 (24: p.4) shows a schematic of the SEI formation.
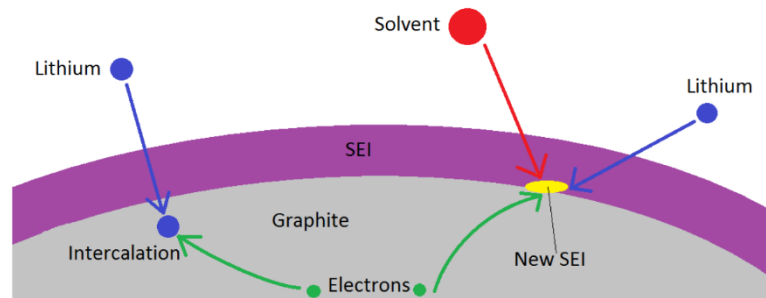

Figure 2 - A schematic of SEI formation (24: p.4)

Due to the high reactivity of the metallic Li produced from Li-Plating, it often also reacts with the electrolyte, adding to the SEI (5,25). Regardless of how it forms, the SEI results in loss of available Li⁺, also leading to capacity losses varying between 10 and 100% during a cell's lifetime (26). It is worth noting however that the SEI is almost completely impenetrable to the chemicals in the electrolyte, meaning that SEI growth after the initial cycle is greatly reduced. Furthermore, it is the electron insulating properties of the SEI itself that allow the battery to function at all.

As with Li-Plating, there are many models describing SEI growth, none of which are agreed to be the best. A comprehensive study of these methods is provided by Pinson et al. (24), and it is shown that there is again a relationship with the Arrhenius law due to the diffusion of Li⁺ being an important factor in both degradation mechanisms. Unlike Li-Plating however, the SEI is proportional to temperature, with growth rate increasing with increasing temperatures. It is also shown that higher C-rates lead to accelerated growth, posing an addition complication for fast charging.

Despite the capacity losses caused by the SEI, it is vital that any method to reduce its effect does not remove it entirely, due to its positive effects. The charging strategies discussed in the following section can be used to limit the growth of the SEI, without preventing its formation.

4. Charging Strategy Solutions

Many solutions are currently being researched, from adding small concentrations of lithium, Li, compounds to the electrolyte (21) to entirely new cell chemistries such as lithium-air and lithium-sulfur (27). This section will present and discuss multiple charging strategies as a solution.

4.1. A Static Approach

4.1.1. CC-CV

The first charging strategy to be discussed is the constant-current constant-voltage (CC-CV) method, where the charging protocol is split into two sections. The majority of papers compare their new findings to data from this technique, and it is therefore crucial to have a full understanding of CC-CV when researching in this field. The reason for this comparison is the widely used application of CC-CV, from mobile phones to EVs (28,29).

Li et al. (30) provide a general schematic of the CC-CV charging strategy, shown in Figure 3 (30: p.1). The cell is initially charged with constant current at a level set by the manufacturer, often to compromise cell degradation and the charging speed. For typical commercial Li^+ batteries, this is usually set at around 0.5 to 1C. For charging EVs at home however, this is often greatly reduced to allow for the limitations in the power available
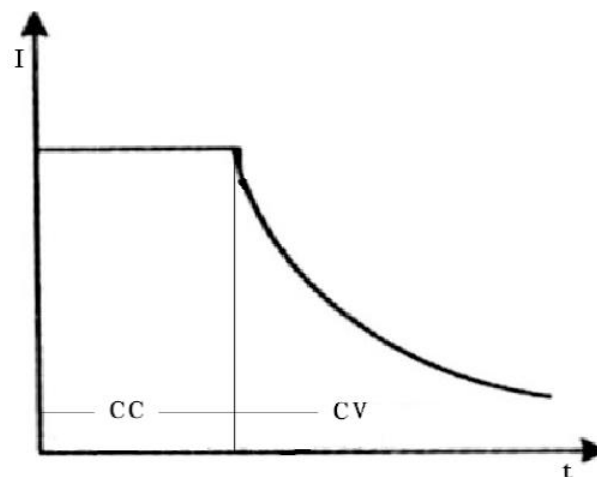
Figure 3 - A general schematic of CC-CV (30: p.1)

from the national grid (31). As the cell reaches V_{max}, the maximum allowable voltage across the cell, (4.2V for Li^+ technologies (31)), the charging switches to a constant voltage stage.

The current is gradually decreased at this constant voltage until a current of around C/10 amperes is being supplied (30). This switch helps to combat the bottleneck problem discussed in section 2. Charging at a high current quickly moves electrons and Li^+ to the surface of the anode where the bottle neck occurs. However, when V_{max} is reached, any further increase in voltage will damage the cell, so the switch maintains the maximum voltage to aid the intercalation process (31) and allow time for it to occur fully. The Li^+ can then intercalate with the anode at the highest allowable current, increasing the diffusion coefficient and charging rate, whilst avoiding overvoltage stresses (14).

This method uses a combination of CC and CV to avoid the negative effects of using a single stage method. As described by Lui et al. (32) if applied from the start, CV would result in extreme currents at the start of the process, leading to potential early onset of Li-plating and a loss of battery capacity. Using CC throughout would lead to the voltage exceeding V_{max} at higher SOCs, resulting in irreversible cell damage. If charging were to be terminated when V_{max} was reached, the battery would never be fully charged, as whilst the surface of the anode will have reached V_{max}, the core will be at some lower voltage.

As with many of the other charging strategies, a relatively large amount of control is required during charging. Abousleiman et al. (29) explains that a Proportional-Integral-Derivative (PID) controller is generally applied to the current during the CV stage of charging, to maintain the voltage across the cell at a fixed level. This is a fact that the majority of papers fail to mention in their discussions, leading to a false idea that the CC-CV strategy is significantly simpler than the other methods. Furthermore, a high level of control is required at the battery pack level. For cells that are connected in series, the voltage shared across each individual cell can fluctuate significantly, due to discrepancies in their internal SOH and, therefore, resistance (33). The BMS is required to monitor each cell, to ensure over-charging does not occur, even within the CV stage.

Depending on the C-rating used during the CC stage, and the SOH of the cell, CC-CV can cause significant temperature rises. For standard charging at rates below 1C, rises between 3 to 7°C have been recorded as reported by Patnaik et al. (31) This is already potentially detrimental to the battery and could lead to an increased rate of SEI formation and reduction in battery-life. Perez et al. (8) use a modelling process to show that the capacity of the cell decreases with increasing C-

Figure 4 - A graph to show how increasing C-rates of the CC stage is detrimental to battery life (8: p1078)

rate, as expected from SEI formation, see Figure 4 (8: p.1078). This is due to Li-plating onset from the increased current rates forming a more drastic build-up of Li⁺ on the surface of the anode.
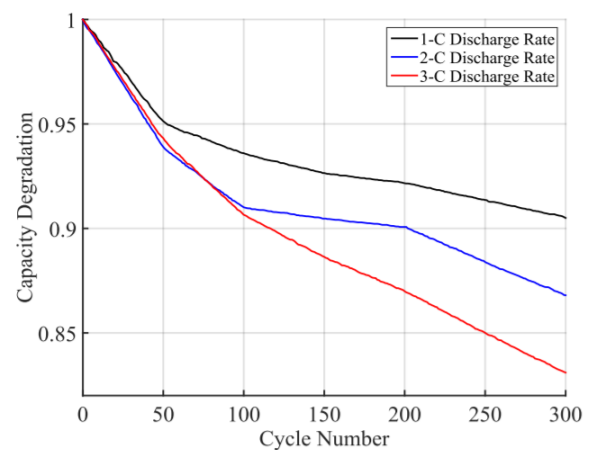
Whilst CC-CV is an elegant solution to safely and fully charge a cell, its fast charging capabilities are limited, and it does nothing to prevent degradation processes such as Li-plating. Its continuing dominance as the go-to charging method in the commercial industry is perhaps perplexing. A full discussion of the future of CC-CV will be provided in section 5 once alternative strategies have been analysed.

4.2. A Dynamic Approach

4.2.1. MCC and MCC-CV

Another widely used charging strategy is multistage CC (MCC). This strategy, along with MCC-CV (2,33), will be discussed here before the focus is turned to future charging strategies.

The MCC strategy is very comparable to the CC-CV method, however, instead of switching to CV as soon as the voltage threshold is reached, the current rate is reduced to lower the voltage. This process repeats until a predefined minimum current stage is reached (32,34). MCC-CV is a combination of these two methods; instead of decreasing the current at constant steps until charging termination, a final CV stage is used to complete the charging process (4). Liu et al. (35) provide general current and voltage profiles for CC-CV (a) and MCC-CV (b), see Figure 5 (35: p.4).
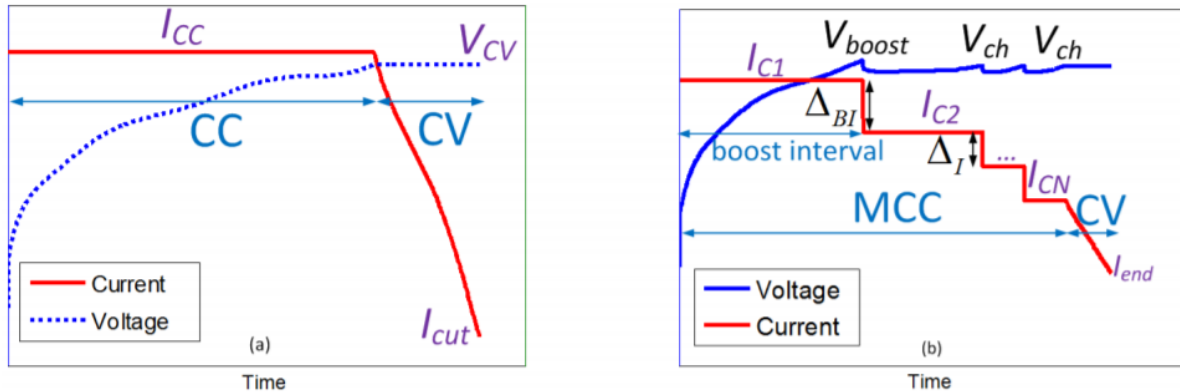

Figure 5-Current and voltage profiles for CC-CV (a) and MCC-CV (b) (35: p.4)

Liu et al. (35), rather uniquely perhaps, define the boost interval as the initial stage in MCC or MCC-CV where the highest current is applied. They emphasise that the charging speed of these profiles are predominantly determined by the C-rating during this first stage, a motion supported

by most other studies (11). Boostcharging is, in fact, a separate charging strategy altogether, (36), which shall be introduced in section 4.2.4.

As clarified by Min et al. (37),the charging strategies MCC and MCC-CV are separated into two categories, voltage-based and SOC-based, describing when the change of current stage is made. The strategy outlined at the start of this section belongs to the voltage-based division, with the current decreasing each time V_{max} is reached, instead of when a specific SOC is reached. Which category the profile depends on is often determined by the modelling technique used to formulate it, see below. As with MCC and MCC-CV, the differences in these strategies will not be discussed here.

Despite its similarities to CC-CV, the dynamic multistage basis of these profile provides many advantages for fast charging and battery cycle life, with many papers showing

Figure 6 – The potential of electrode surfaces' during charging CC-CV (a) and MCC-CV (b) (5: p.1390)

a significant increase in performance in these areas (12,37,38). As with all charging, the rate at which the battery is charged will decrease as the SOC increases, and this is a significant issue with CC-CV. As expected, the CV stage take the longest (35), and these dynamic profiles are a way of increasing the time spent charging at CC (30) and, as described by Dusmez et al. (34), the change increases the charge expectance rate of the battery.

Despite the more sophisticated approach of these dynamic profiles, there is still conflict and uncertainty surrounding their benefits to the charging process. Lui et al. (32) states that the charging time MCC will in fact usually be longer than that of CC-CV when the same initial current is used. Furthermore, Zhang (5) demonstrated that, during his experiments, the potential of the negative carbon anode ($E_{(-)}$) drops below 0V; a condition which will bring on the onset of Li-plating, reducing the battery's capacity, see Figure 6b (5: p.1390). This condition does not occur for CC-CV in this study.
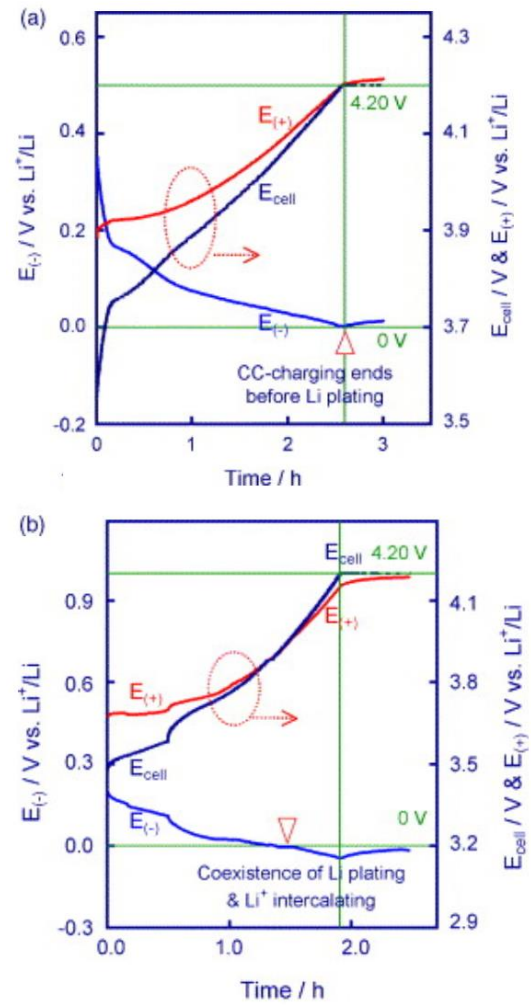
As with CC-CV, the specifics of the MCC and MCC-CV profiles must be chosen by the cell manufacturer. For each of these profiles, the CV stage, if used at all, must commence at a relatively fixed point, V_{max}, which is set due to the cell chemistry. This leaves one major variable to be chosen for the CC-CV profile, the initial C-rate, and this is simply chosen to reflect a trade-off between capacity loss and charging speed. Similarly, the current of the MCC and MCC-CV profiles must drop when this V_{max} value is recorded across the cell. Unlike CC-CV however, the current at the multiple CC stages and variables must be determined; this remains true for most dynamic profiles.

It is widely accepted that for these profiles, selecting the optimum parameters can drastically improve the charging performance (4). It should be noted that for Zhang's (5) study, Figure 6 (5: p.1390) above, the CC-CV profile was optimised, however the variables for the MCC-CV profile were chosen rather arbitrarily. Furthermore, the CC-CV profile used had an overall C-rating of 0.33C, whist the MCC-CV profile's rating was 0.5C. Optimised profiles will now be presented, and the methods in which they are selected introduced, so an accurate comparison of CC-CV and MCC-CV can be formulated.

The algorithms and models often used to optimise these dynamic profiles are often based on a model of a battery, many of which exist (8,39), see section 2. The charging performance of the optimised profile is then compared with other profiles using the very same battery model. An identical algorithm would produce a different profile if it was based on a different battery model, as it would do if the algorithm was using actual cell data. Nevertheless, discrepancies in these models shall be assumed to be negligible, however it should be noted that for a more rapid development of an optimum dynamic charging strategy, a more accurate battery model is required. Without such models, the battery can only be evaluated using real cyclic testing, often taking more than eight years to accurately show the battery's life cycle (40).

Aside from Lui et al. (32) and Zhang (5), the majority of studies have seen an increase in charging performance for all MCC and MCC-CV profiles compared with CC-CV. Yi-Hwa et al. (11) use the Ant Colony System (ACS) algorithm in combination with an unspecified battery model to form their optimum MCC profile. Unlike other papers, Yi-Hwa et al. (11) acknowledge the limitations of the battery model and incorporate a real-life battery tester into the data.

The ACS algorithm was inspired by observations of the foraging characteristics of a real ant colony and incorporates a positive feedback loop to quickly find the optimum solution. Artificial ants are used to find the 'path' of least cost, i.e. least battery degradation, based on the initial constraint of reaching 70% SOC in 30 minutes. The results show a profile which can indeed achieve this, whist maintaining 85% of its original capacity after 300 cycles, compared to CC-CV's 80%.

In another paper, Yi-Hwa et al. (41) use the Taguchi approach, (another algorithm implementing a cost function that is more specific to engineering), with similar results. The battery is charged to 75% capacity in 40 minutes. The team suggest that this profile can achieve 60% more cycles than CC-CV at the same C-rating before the same level of capacity loss is recorded, however, the profile is only tested for 181 cycles, leaving the long-term performance unclear. The temperature increase per charge cycle is marginally smaller with the MCC profile than in CC-CV, leading to slower SEI development and the longer cycle life. This discrepancy in the type of data discussed and the method in which they are formatted, even between two papers from the same group, show that standardisation is drastically required in this field of research. This line of thought will be further discussed in section 5.

Abdel-Monem et al. (4) tested eight different profiles at 25°C, with a focus on capacity retention after multiple cycles. Each profile in this study had the variables discussed at the start of this paper chosen without optimisation. They found that after 300 cycles, CC-CV had retained 99% of its capacity, compared to 97.5% an MCC-CV with the same initial current. However, the rate at which the CC-CV profile lost capacity then drastically increased, and by 1700 cycles, it had lost over 24% of its original capacity, compared to just over 12% for the MCC-CV profile.

Despite the conclusions of Lui et al. (32) and Zhang's (5) study, it is apparent from the literature that the ability to fine tune parameters of both MCC and MCC-CV can simultaneously increase charge time and cell life when compared to CC-CV. The optimised profile only needs to be found once, making it a fully viable and commercial approach. However, it seems clear that a new approach is required before a significant increase in C-rating can be seen.

4.2.2. Pulse-charging

Moving beyond more conventional methods, pulse-charging is a strategy where controlled current pulses are applied to the cell (42), and already has a large commercial use in portable electronics (1,29). As described below, the pulses can be overlaid on any existing current profile. Figure 7 (29: p.4) shows a time pulse charging (TPC) strategy. After 55 seconds of charging at a predetermined current, the current reduces to zero for 5 seconds. In this example, the pulses are overlaid on a MCC profile, where the current decreases by 0.02A each time the voltage reaches V_{max}.

Despite being brief, the periods of zero current allow the battery's internal mechanism to relax (29). This allows the Li$^+$ within the electrolyte to diffuse and provides time for the ions to intercalate with the anode (43). It is this rest
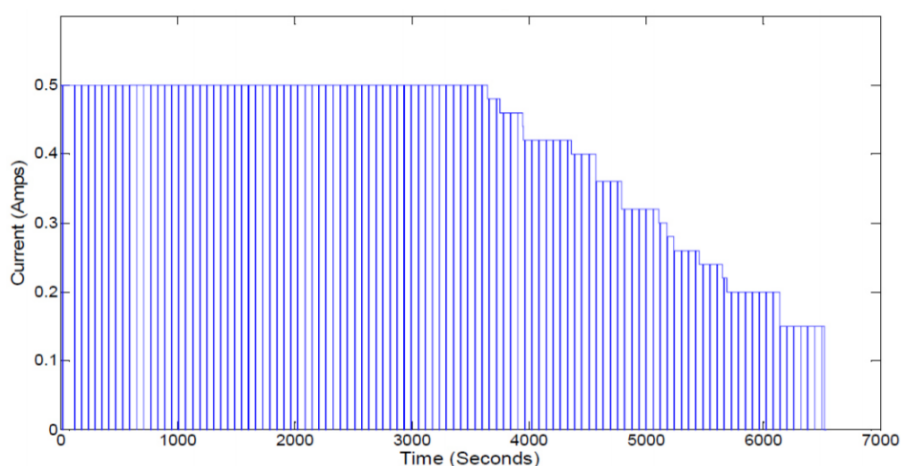

Figure 7 - The complete current profile of a specific TPC charging strategy (29: p4)

time that significantly slows the formation of Li-plating, therefore greatly increasing the cycle-life of the battery (42).

The pulse-charging strategy can be separated into many categories of their own, determined by the pulse pattern applied to the original profile. For example, in the negative pulse strategy (NP), the battery is momentarily discharged instead of returning to zero current (4), and a technique called cold derating (CD) utilises the pulse pattern to ensure the voltage at the anode cannot become negative, helping to aid the prevention of Li-plating (17).

Schindler et al. (17) note that there is a lack of understanding of the electrochemical effects of using many of the specific patterns, and the how each one will change the properties of the specific strategy it is applied to. Furthermore, each pattern may perform differently depending on the frequency, amplitude and number of pulses that are used (4). Whilst Schindler et al. (17) and others dedicate experiments and literary reviews to finding the optimum way to apply pulse charging, there are many which suggest that no such significant optimisation even exists (29,43).

It is clear the intricacies of pulse-charging are a huge area of ongoing area of research. As such however, the details cannot be discussed in length here. The studies instead will be reviewed and discussed to reach a conclusion of the potential impact of pulse-charging as a whole for EVs.

Abousleiman et al. (29) experiment using the TPC profile shown in Figure 7 (29: p.4) above. They found that, using identical initial C-rates, (0.625C), the TPC profile charged the battery one minute faster than CC-CV competitor. This is despite the pulses essentially meaning that the battery was not being charged for over 8% of the time. The team also noted that the TPC profile resulted in less temperature rise than conventional CC-CV did. They reasoned that this was due to the rest times, showing how this method is less aggressive on the battery, and would ultimately lead to a longer cycle-life.

Two of the profiles tested by Abdel-Monem et al. (4) were CC-CV overlaid with NPs. These strategies performed significantly better than all others and retained approximately 89% of their capacity after 1700 cycles. This compares to just 76% for a CC-CV profile with the same overall C-rating. Abdel-Monem et al. (4) also tested a MCC profile with similar overlaid NPs, which lost 84% of its capacity after the same number of cycles. Moreover, this MCC profile preformed worse than its counterpart profile without negative pulses, losing just 87% of its capacity. This shows that NPs, and perhaps pulses in general, could have adverse effects on the battery performance in certain situations. As emphasized by Liang-Rui et al. (44), finding the optimum variables for these dynamic profiles is a top priority for future research.

Other studies, focusing more on fast charging and less on degradation, have shown an improvement of 14% in charge time compared to the same CC-CV profile without pulses (43). It could be argued that the lack of clarity and understanding in the specific effects of certain pulses is a primary reason as to why pulse-charging has not been adopted by the automotive industry. Furthermore, should a complete model be developed to obtain the optimum variables, it is likely that significantly lower charge times would be achieved with little compromise to cycle-life. These results could be enough to encourage the EV market to switch charging strategy.

4.2.3. CT-CV

With the effects of temperature so apparent on battery performance and longevity, it would seem intuitive that a temperature-controlled stage be introduced to the charging. Patnaik et al. (31) appear to be the first and only team to be developing and testing a charging strategy with a constant temperature (CT) stage.

Despite the name, the profile developed does not maintain a constant temperature throughout charging. Instead, using a PID controller, it is ensured that the maximum temperature rise, ΔT_{max}, matches that of a standard CC-CV profile. The controller could be integrated with the BMS in an EV, and Patnaik et al. (31) even use the same PID system implemented for the existing CV stage, making this strategy a feasible option for car manufacturers.

Figure 8 The current and temperature properties of CC-CV and CT-CV (31: p.1061)

Patnaik et al. (31) reason that the degradation caused by CC-CV is low enough that the cycle-life is still usable for many applications, including EVs. As temperature is a key factor in degradation, controlling the maximum temperature should halt many of the degradation mechanisms, and allow a current profile to be developed, focusing only on increasing the charging speed.

As shown in Figure 8 (31: p.1061), the team initially apply a high current to the cell, 2C, such that ΔT_{max} is reached at an earlier state. Before entering the CV stage, the current decays at an exponential rate to ensure this high current is not present at a high SOC. This profile charges the cell 20% faster than the CC-CV, and the papers suggests that the same amount of degradation will occur, and the cycle-life's will be comparable. The team, however, neglect other drivers of battery degradation, such as the voltage at the anode. Furthermore, no mention is made of the varying effects of temperature and current rates at different SOCs, and no cycle analysis is performed to confirm the battery's cycle-life is comparable to that of CC-CV's.
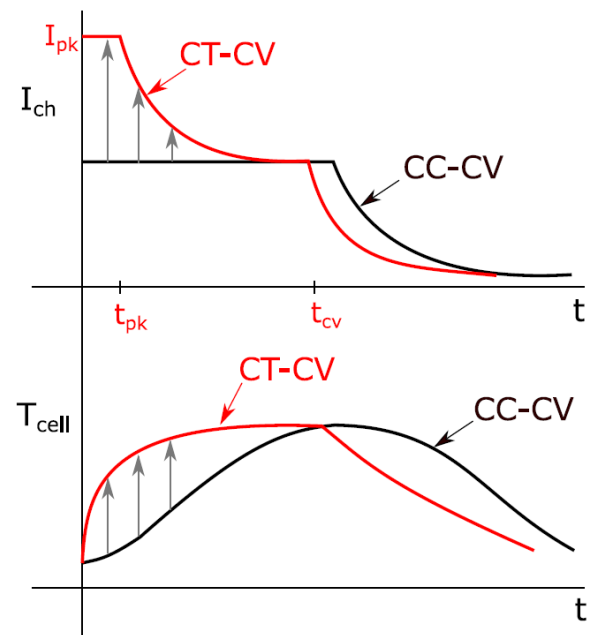
Nevertheless, it is the active control of the negative impacts on the battery that is so novel and could allow future developers to adapt the variables of their profiles with a focus on C-rating rather than battery degradation. The method could surely be combined with the other profiles discussed in this section and pave the way for a strategy that vastly increases the C-rating.

4.2.4. Other Charging Strategies

For a more complete review of the research into charging strategies as a solution for fast charging EVs, it should be noted that there are many more profiles than those discussed above. To fully demonstrate the progress being made in this field, the most promising of these will be introduced here and discussed in brief.

As well as investigating MCC-CV, see section 4.2, Zhang (5) also experimented with a constant power- constant voltage strategy, CP-CV. For this profile, the current is initially set at a value higher than CC-CV and MCC-CV, the voltage begins to increase until it reaches 4.2V and enters the CV stage. During the first stage, the current will gradually decrease due to the relationship between voltage, current and power. Zhang (5) cyclically tested his profiles at 0.5 and 1C, and found that at 1C, the capacity fade was significantly lower than that of both CC-CV and MCC-CV. This is due to the significantly low currents at high SOC just prior to the CV stage, preventing the onset of Li-plating, and demonstrates a great potential for CP-CV at higher C-rates.

In recent years, the Sinusoidal-Ripple-Current Charging Strategy (SRC) has been developed (44,45). The method is highly comparable to the pulse method, except the discrete pulses are replaced with a continuous sinusoidal wave. These appear to further increase the advantages seen when using pulses. When charging fully in around an hour, Liang-Rui et al. (44) demonstrated a 17% improvement in charge time and, simultaneously, a 16.1% increase in battery cycle-life when compared to CC-CV. When compared to the conventional pulse strategy, a marginal decrease in charge time of 0.24% was observed and a decrease of over 16% was seen in the maximum temperature rise. It is perhaps promising to see improvements to more advanced strategies, such as current-pulses, already being established; however, it could be argued that they are currently too marginal to be deemed significant.

Finally, boostcharging is a more established method with the highest C-ratings reported in this review (36). The strategy is essentially CV-CC-CV, starting with a very short period of CV, often at 4.3V, just above the recorded maximum allowable voltage for Li$^+$ batteries, and extremely high current rates of 5C and up. This approach, as with CT-CV, utilises the fact that these high currents are much more detrimental at a higher SOC, and it is reported that this boost charging strategy can charge a fully discharged battery to 33% of its capacity in 5 minutes (36). This would provide an EV with approximately 100 miles of range in the time it would take a conventional car to refuel. The caveat is that the battery must be fully discharged; if the boost stage was applied at a random SOC, this method might not function, or the battery could be destroyed. (46)

It is clear that, whilst no single profile stands out as a full solution, there has been significant development in this field. A new approach, or even a combination of strategies, could indeed aid the solving of the fast charging conundrum in EVs.

5. Further Discussion

Results of specific charging methods have been reviewed, compared and discussed in section 4 as they have been presented, and a more generalised discussion for the impact on the EV market will be presented here.

A major limitation in this field is the difficulty to compare specific experimental results. As can be seen by the results presented in this review, and as highlighted by Wu et al. (12), many studies test at one single temperature, ignoring the range of environments an EV must operate in. Furthermore, those that do test at multiple temperatures select them randomly, so the results are still not comparable with other studies using different values. Many studies also choose to describe the currents used in Amperes, not C-rate, and those that do again select arbitrary values, making even the effects of profiles on degradation difficult to compare (4). As such, it is nearly impossible to suggest a best all-round strategy based purely on empirical data, despite its abundance. Standardisation may be challenging in an area where research is predominantly pushed and funded by competing companies, but some level of cooperation is required to allow the results of such studies to be accurately and fairly compared.

A further issue with comparing strategies, even those of the same general type, is due to the large number of variables of each profile. Each profile will have multiple differences, often in multiple stages, in frequency, amplitude or duration, even if the general shape/classification is the same. This makes it extremely difficult to isolate the cause of any perceived improvements. More in depth research should be done to isolate the impact of adjusting one of these variables at a time.

As described by Yong et al. (7), as of 2015, CC-CV was the preferred charging strategy used for large Li$^+$ batteries such as those used in EVs. This choice is not due to CC-CV's fast charging capabilities, nor is it to prevent degradation mechanisms such as Li-plating or SEI formation. As discussed in section 4, CC-CV does not even drastically simplify the control systems required during charging. It appears that the true reason for the vast commercial use of CC-CV is the lack of research into new strategies, and the effort required to perform cycling testing. Fortunately, research into other charging strategies has progressed since 2015.

It seems that there is overwhelming evidence that every charging strategy presented in this review outperforms CC-CV, with, for example, SRC providing a simultaneous increase in cycle-life and

decrease in charge time of over 16% . The profiles reviewed in this paper have much potential to replace CC-CV in the near future.

Nevertheless, using batteries with a modified cell chemistry, C-rates of 10C were recorded using the CC-CV method by Zaghib et al. (47) At these rates, the cells maintained near full capacity over 20,000 cycles, and would allow for charging in just 6 minutes. These batteries, however, are not currently suitable for EV application, as they have a 32.5% reduction in total capacity compared to standard Li^+ batteries. This capacity loss is caused by the change of anode material to $Li_4Ti_5O_{12}$ and would result in the EV's range being reduced from around 300 km to 200 km (47). Furthermore, as explained by Li (48), there are other issues with this technology, from increased operating temperatures, potential leading to an autocatalytic decomposition of the electrolyte, and a limited understanding of how the battery will behave during the large power supply required during rapid acceleration of the vehicle. It seems clear that a vast amount of research and development is required into new cell chemistries before they are applicable for commercial use and, as such, new charging strategies may provide a more suitable solution to the fast charging problem in the not so distant future. Even if a complete overhaul of current Li^+ technology was to take place, research into these charging strategies may be applicable to them too, further increasing their performance.

Strategies with C-ratings of 1C, capable of charging an EV in one hour, have been available for many years without causing significant life-cycle loss. Yet charging at home still requires up to eight hours. There is a need for grid updates in these area, and development of these profiles can currently only be applied to commercial charging stations. To fully capitalise on any developments in this field, they need to be complemented by an ability to improve existing grid infrastructure.

Unfortunately, no profile has yet been developed with C-ratings capable of fully charging a Li^+ battery powered EV in the time it would take to refill a petrol or diesel car's tank. It is clear, however, that, with greater standardisation, focus on optimising existing strategies and additional support from industry, a change in charging strategy could help make fast charging a reality for EVs.

6. Conclusions

In this literary review, the difficulties of fast charging EVs has been revealed and multiple charging strategies have been presented as a solution to the compromise between cycle-life and charging time. A discussion has been made throughout, primarily on the general application of the research into charging strategies as a solution to the problem, but also on the effectiveness of individual current profiles. For clarity, the most significant conclusions are outlined below.

➢ The primary challenge for fast charging in EVs is to achieve low charging times without the significant increase in the rate of SEI formation, Li-plating and, ultimately, battery life-cycle reduction.

➢ CC-CV is an elegant solution to this problem; however, it will not be able to provide the charging times required for EVs. It is still used widely by the industry predominantly due to the lack of understanding and development of other strategies.

➢ New charging strategies possess the ability to not only increase the charging rate of current Li^+ batteries, but also enhance their life-cycle performance.

➢ Using algorithms and models to select the variables of dynamic profiles is of great importance, with an optimum MCC profile achieving 70% SOC in 30 minutes.

➢ The pulse-charging technique is also promising, with the majority of studies showing a better performance in both cycle-life and charge time.

➢ Active control can be used for more than just the CV stage, and new ideas for the applications of control, such as CT, may result in the overall optimum charging strategy.

➢ More work should be done into finding a complete mathematical model of the battery, applicable at all temperatures, to aid the finding of these optimised strategies.

➢ The field requires more standardisation to allow for new profiles to be compared to their old counterparts and the effectiveness of minor alterations to be measured.

➢ Improvements to the network are required, especially for home charging, for the benefits of new charging strategies to come to fruition. With developments such as this, utilising the most promising strategies will certainly aid further development of fast charging of EVs.

7. References

(1) Cowell R, Ellis G, Sherry-Brennan F, Strachan PA and Toke D. Energy transitions, sub-national government and regime flexibility: How has devolution in the United Kingdom affected renewable energy development? *Energy Research & Social Science.* 2017; 23 169-181. Available from: doi: 10.1016/j.erss.2016.10.006 .

(2) *New & Used Electric Cars | Tesla UK.* Available from: https://www.tesla.com/en_GB/inventory/new/ms [Accessed Dec 1, 2018].

(3) *Formula 1 technology spins off into the real world.* Available from: https://www.newscientist.com/gallery/dn16689-from-the-race-track-to-space-and-hospitals/ [Accessed Nov 11, 2018].

(4) Abdel-Monem M, Trad K, Omar N, Hegazy O, Van DB and Van Mierlo J. Influence analysis of static and dynamic fast-charging current profiles on ageing performance of commercial lithium-ion batteries. *Energy.* 2017; 120 179-191. Available from: doi: 10.1016/j.energy.2016.12.110 .

(5) Zhang SS. The effect of the charging protocol on the cycle life of a Li-ion battery. *Journal of Power Sources.* 2006; 161 (2): 1385-1391. Available from: doi: 10.1016/j.jpowsour.2006.06.040 .

(6) Manzetti S, Mariasiu F. Electric vehicle battery technologies: From present state to future systems. *Renewable and Sustainable Energy Reviews.* 2015; 51 1004-1012. Available from: doi: 10.1016/j.rser.2015.07.010 .

(7) Yong JY, Ramachandaramurthy VK, Tan KM and Mithulananthan N. A review on the state-of-the-art technologies of electric vehicle, its impacts and prospects. *Renewable and Sustainable Energy Reviews.* 2015; 49 365-385. Available from: doi: 10.1016/j.rser.2015.04.130 .

(8) Perez A, Quintero V, Jaramillo F, Rosas H, Diego J, Orchard M, et al. Characterization of the degradation process of lithium-ion batteries when discharged at different current rates. 2018; 232(8) 1075–1089.

(9) Omar N, Daowd M, Bossche P, Hegazy O, Smekens J, Coosemans T, et al. Rechargeable Energy Storage Systems for Plug-in Hybrid Electric Vehicles-Assessment of Electrical Characteristics. *Energies.* 2012; 5 (8): 2952-2988. Available from: doi: 10.3390/en5082952 .

(10) Frank J. Puglia, William Alexander McPhee, Stuart Santee, Boris Ravdel, Joseph S. Gnanaraj, Malgorzata K. Gulbinska, et al. *Lithium-ion Battery Materials and Engineering.* Green Energy and Technology DE: Springer Verlag; 2014.

(11) Yi-Hwa Liu, Jen-Hao Teng and Yu-Chung Lin. Search for an optimal rapid charging pattern for lithium-ion batteries using ant colony system algorithm. *Industrial Electronics, IEEE Transactions on.* 2005; 52 (5): 1328-1336. Available from: doi: 10.1109/TIE.2005.855670 .

(12) Wu X, Hu C, Du J and Sun J. Multistage CC-CV Charge Method for Li-Ion Battery. *Mathematical Problems in Engineering.* 2015; 2015 Available from: doi: 10.1155/2015/294793 .

(13) Perez A, Quintero V, Jaramillo F, Rosas H, Diego J, Orchard M, et al. Characterization of the degradation process of lithium-ion batteries when discharged at different current rates. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering.* 2018; 232 (8): Available from: doi: 10.1177/0959651818774481 .

(14) Li L, Tang X, Qu Y and Liu H. *CC-CV charge protocol based on spherical diffusion model.* English ed. ed. Changsha, Hunan : 2011.

(15) Acha S, Green TC and Shah N. *Optimal charging strategies of electric vehicles in the UK power market.* 2011.

(16) Aggeler D, Canales F, Zelaya H, Parra DL, Coccia A, Butcher N, et al. *Ultra-fast DC-charge infrastructures for EV-mobility and future smart grids.* 2010.

(17) Schindler S, Bauer M, Cheetamun H and Danzer MA. Fast charging of lithium-ion cells: Identification of aging-minimal current profiles using a design of experiment approach and a mechanistic degradation analysis. *Journal of Energy Storage.* 2018; 19 364-378. Available from: doi: 10.1016/j.est.2018.08.002 .

(18) Remmlinger J, Tippmann S, Buchholz M and Dietmayer K. Low-temperature charging of lithium-ion cells Part II: Model reduction and application. *Journal of Power Sources.* 2014; 254 268-276. Available from: doi: 10.1016/j.jpowsour.2013.12.101 Available from: https://www.sciencedirect.com/science/article/pii/S0378775313020909 .

(19) Doyle M. Modeling of Galvanostatic Charge and Discharge of the Lithium/Polymer/Insertion Cell. *Journal of The Electrochemical Society.* 1993; 140 (6): 1526. Available from: doi: 10.1149/1.2221597 .

(20) Ge H, Aoki T, Ikeda N, Suga S, Isobe T, Li Z, et al. Investigating lithium plating in lithium-ion batteries at low temperatures using electrochemical model with NMR assisted parameterization. *Journal of the Electrochemical Society.* 2017; 164 (6): A1060. Available from: doi: 10.1149/2.0461706jes .

(21) Zheng J, Xu W. Electrolyte additive enabled fast charging and stable cycling lithium metal batteries. *Nature Energy.* 2017; 2 (3): Available from: doi: 10.1038/nenergy.2017.12 .

(22) Peled E. The Electrochemical Behavior of Alkali and Alkaline Earth Metals in Nonaqueous Battery Systems—The Solid Electrolyte Interphase Model. *Journal of the Electrochemical Society.* 1979; 126 (12): 2047. Available from: doi: 10.1149/1.2128859 .

(23) Vetter J, Novák P, Wagner MR, Veit C, Möller K-, Besenhard JO, et al. Ageing mechanisms in lithium-ion batteries. *Journal of Power Sources.* 2005; 147 (1-2): 269-281. Available from: doi: 10.1016/j.jpowsour.2005.01.006 .

(24) Pinson MB, Bazant MZ. Theory of SEI Formation in Rechargeable Batteries: Capacity Fade, Accelerated Aging and Lifetime Prediction. *Journal of the Electrochemical Society.* 2013; 160 (2): A250. Available from: doi: 10.1149/2.044302jes .

(25) Liu Q, Du C, Shen B, Zuo P, Cheng X, Ma Y, et al. Understanding undesirable anode lithium plating issues in lithium-ion batteries. *RSC Advances*. 2016; 6 (91): 88683-887. Available from: doi: 10.1039/c6ra19482f .

(26) Anseán D, González M, Viera JC, García VM, Blanco C and Valledor M. Fast charging technique for high power lithium iron phosphate batteries: A cycle life analysis. *Journal of Power Sources*. 2013; 239 9-15. Available from: doi: 10.1016/j.jpowsour.2013.03.044 .

(27) Marinescu M, O'Neill L, Zhang T, Walus S, Wilson T and Offer G. *Irreversible vs Reversible Capacity Fade of Lithium-Sulfur Batteries during Cycling: The Effects of Precipitation and Shuttle*. Electrochemical Society; 2018.

(28) Amietszajew T, Mcturk E, Fleming J and Bhagat R. Understanding the limits of rapid charging using instrumented commercial 18650 high-energy Li-ion cells. *Electrochimica Acta*. 2018; 263 346-352. Available from: doi: 10.1016/j.electacta.2018.01.076 .

(29) Abousleiman R, Al-Refai A and Rawashdeh O. *Charge Capacity Versus Charge Time in CC-CV and Pulse Charging of Li-Ion Batteries*. 2013. Available from: https://saemobilus.sae.org/content/2013-01-1546.

(30) Li S, Zhang C and Xie S. Research on fast charge method for lead-acid electric vehicle batteries. *2009 International Workshop on Intelligent Systems and Applications, ISA 2009, May 23, 2009 - May 24, 2009*. Wuhan, China: IEEE Computer Society; 2009. pp. Huazhong Normal University; Huazhong University of Science and Technology; Hubei University of Technology; IEEE Harbin Section. Available from: http://dx.doi.org/10.1109/IWISA.2009.5073068. Available from: 10.1109/IWISA.2009.5073068.

(31) Patnaik L, Praneeth, A. V. J. S and Williamson SS. A Closed-Loop Constant-Temperature Constant-Voltage Charging Technique to Reduce Charge Time of Lithium-Ion Batteries. *IEEE Transactions on Industrial Electronics*. 2019; 66 (2): 1059-1067. Available from: doi: 10.1109/TIE.2018.2833038 Available from: https://ieeexplore.ieee.org/document/8353785 .

(32) Liu K, Li K, Peng Q and Zhang C. A brief review on key technologies in the battery management system of electric vehicles. 2018; .

(33) Cassani PA, Williamson SS. Design, Testing, and Validation of a Simplified Control Scheme for a Novel Plug-In Hybrid Electric Vehicle Battery Cell Equalizer. *IEEE Transactions on Industrial Electronics*. 2010; 57 (12): 3956-3962. Available from: doi: 10.1109/TIE.2010.2050750 Available from: https://ieeexplore.ieee.org/document/5475245 .

(34) Dusmez S, Cook A and Khaligh A. *Comprehensive analysis of high quality power converters for level 3 off-board chargers*. 2011.

(35) Liu K, Zou C, Li K and Wik T. Charging Pattern Optimization for Lithium-Ion Batteries with An Electrothermal-Aging Model. 2018; .

(36) Notten PHL, Veld, J. H. G. O. and Beek JRG. Boostcharging Li-ion batteries: A challenging new charging concept. *Journal of Power Sources*. 2005; 145 (1): 89-94. Available from: doi: 10.1016/j.jpowsour.2004.12.038 .

(37) Min H, Sun W, Li X, Guo D, Yu Y, Zhu T, et al. Research on the Optimal Charging Strategy for Li-Ion Batteries Based on Multi-Objective Optimization. *Energies.* 2017; 10 (5): 709. Available from: doi: 10.3390/en10050709 .

(38) Ikeya T, Sawada N, Murakami J, Kobayashi K, Hattori M, Murotani N, et al. Multi-step constant-current charging method for an electric vehicle nickel/metal hydride battery with high-energy efficiency and long cycle life. *Journal of Power Sources.* 2002; 105 (1): 6-12. Available from: doi: 10.1016/S0378-7753(01)00907-7 .

(39) Santhanagopalan S, Guo Q, Ramadass P and White RE. Review of models for predicting the cycling performance of lithium ion batteries. *Journal of Power Sources.* 2006; 156 (2): 620-628. Available from: doi: 10.1016/j.jpowsour.2005.05.070 .

(40) *Why do Li-ion Batteries die? And how to improve the situation?* Directed by: Professor Jeff Dahn. Waterloo Institute for Nanotechnology; 2013.

(41) Yi-Hwa Liu, Yi-Feng Luo. Search for an Optimal Rapid-Charging Pattern for Li-Ion Batteries Using the Taguchi Approach. *Industrial Electronics, IEEE Transactions on.* 2010; 57 (12): 3963-3971. Available from: doi: 10.1109/TIE.2009.2036020 .

(42) Amanor-Boadu J, Guiseppi-Elie A and Sánchez-Sinencio E. The Impact of Pulse Charging Parameters on the Life Cycle of Lithium-Ion Polymer Batteries. *Energies.* 2018; 11 (8): 2162. Available from: doi: 10.3390/en11082162 Available from: https://search.proquest.com/docview/2108521280 .

(43) Liang-Rui Chen. Design of Duty-Varied Voltage Pulse Charger for Improving Li-Ion Battery-Charging Response. *Industrial Electronics, IEEE Transactions on.* 2009; 56 (2): 480-487. Available from: doi: 10.1109/TIE.2008.2002725 .

(44) Liang-Rui Chen, Shing-Lih Wu, Deng-Tswen Shieh and Tsair-Rong Chen. Sinusoidal-Ripple-Current Charging Strategy and Optimal Charging Frequency Study for Li-Ion Batteries. *Industrial Electronics, IEEE Transactions on.* 2013; 60 (1): 88-97. Available from: doi: 10.1109/TIE.2012.2186106 .

(45) Vadivelu S. *Investigation of sinusoidal ripple current charging techniques for Li-ion cells.* 2016.

(46) Chu Z, Feng X, Lu L, Li J, Han X and Ouyang M. Non-destructive fast charging algorithm of lithium-ion batteries based on the control-oriented electrochemical model. *Applied Energy.* 2017; 204 1240-1250. Available from: doi: 10.1016/j.apenergy.2017.03.111 .

(47) Zaghib K, Dontigny M, Guerfi A, Charest P, Rodrigues I, Mauger A, et al. Safe and fast-charging Li-ion battery with long shelf life for power applications. *Journal of Power Sources.* 2011; 196 (8): 3949-3954. Available from: doi: 10.1016/j.jpowsour.2010.11.093 .

(48) Li Y. A review of recent research on nonequilibrium solid solution behavior in LiXFePO4. *Solid State Ionics.* 2018; 323 142-150. Available from: doi: 10.1016/j.ssi.2018.05.026 .

2018-2019 ME3 LITERATURE RESEARCH PROJECT

Meeting Log

STUDENT:	Jake Reynolds	SUPERVISOR:	Monica Marinescu
TITLE:	Fast Charging of EVs		

Meeting	Date	Student Signature	Supervisor Signature
Week 2	10th Ot 18		
Week 5	7th Nov 18		
Week 7	14th Nov 18		
Week 9	30th Nov 18		