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How Different Parameters Affect Fast Charging of LiFePO4 Batteries in Electrical Vehicles

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ABSTRACT

This review paper provides a comprehensive analysis of electric vehicles (EVs) and the various factors influencing fast charging technology. The surge in EV adoption has necessitated advancements in charging infrastructure, particularly in fast charging solutions. We delve into the technical aspects of fast charging, including its impact on battery life, charging station architecture, power grid integration, and charging protocols. Moreover, we discuss the influence of battery chemistry, temperature management, and charging infrastructure on the efficacy of fast charging. By synthesizing current research findings and industry trends, this paper offers insights into the challenges and opportunities for enhancing fast charging efficiency and accessibility, thereby accelerating the widespread adoption of electric vehicles.

Introduction

Climate change presents one of the greatest challenges to modern society, threatening everything from modern agriculture to liveable regions on the globe for both animals and humans. This is in large part fuelled by large and increasing emissions of greenhouse gases due to human activity. These gases are very efficient at trapping heat in the atmosphere, and so greater concentrations of these gases leads to a warmer world. Automobiles have been a great factor in emitting these greenhouse gases; hence it is clear that reducing greenhouse gas emissions from consumer vehicles will significantly reduce the future heating effect and help to prevent climate crisis.

The International Energy Agency recently proposed the "Net Zero Emissions by 2050 Scenario" in which they present a possible route for the world to achieve net zero carbon emissions by 2050. (IEA, 2023) Similarly, the EU has pledged to achieve net zero greenhouse gas emissions by 2050 (Commission, n.d.), with each of the EU Member States having developed national strategies to be 'climate-neutral'. For any of these strategies to be successful, it will be necessary to move away from fossil fuel powered consumer vehicles.

As a result, there has been huge growth in the production of electrical vehicles (EV) by automobile manufacturers and in research into improving battery technology. To make consumers switch to electric vehicles, there are two major sticking points. Firstly, consumers typically cite range anxiety as a key consideration for not moving to EVs. It is caused by the fear that the driver's EV will not have enough battery charge to reach its destination. Secondly, consumers state that charging times are far too high for electric vehicles, given that a typical gasoline vehicle can be refuelled in around 10 minutes. As a result, there is great interest in improving the charging efficiency of electric batteries to close the gap in refuel times between electric and conventional combustion-powered vehicles. In this review, we choose to focus on the second of these points, specifically on the main physical considerations associated with charging efficiency.

Lithium-ion (Li-ion) batteries are the dominant battery composition for EVs due to their higher energy density, long shelf-lives and rapid charging capabilities. However, even within Li-ion batteries there are a variety of different chemistries (Tran M-K D. A.). Of these, automotive companies favour lithium iron phosphate (LFP or $LiFePO_4$) batteries as they are non-toxic since they do not contain harmful heavy metals such as cobalt or nickel as many other Li-ion battery compositions do, and they also are very efficient with round-trip energy efficiencies of over 95%. For these reasons, in 2022, market share for LFP batteries for EV batteries increased up to 31%, with the two largest EV manufacturers, Tesla and BYD, having purchased 68% of the available LFP batteries. As a result, we focus only on LFP batteries specifically in this review.

Although Li-ion batteries are the most promising candidate for powering modern EVs, charging times remain a concern. When attempting to charge batteries more rapidly, there are trade-offs, as more aggressive charging tends to degrade battery health, which limits battery storage capacity and shelf life. Charging Li-ion batteries as quickly as possible subject to maintaining good battery health is the subject of intense research. This review explores the main physical considerations affecting charging times of Li-ion batteries with these constraints over the past two decades.

Definition of Terms

Before investigating the different aspects to maximise the EV battery fast charging, this section provides a comprehensive list of subject specific terms.

Fast Charging

The question focuses on 'fast charging', and for EVs, it is a technique of charging that allows the battery to be replaced quickly with a significantly high electrical power being converted and transmitted through the cable. The power varies for fast charge points: the input/output nominal power of either 43kW or 50kW is delivered through a direct current (DC) via three-phrase electric power. (Peng Rong & Pedram, 2006) Higher-power charging stations that can transfer electricity at a considerably faster rate than conventional charging methods are usually used in this process. These quick charging stations enable drivers to swiftly recharge their EVs and resume their journey with the least amount of downtime by providing a sizable quantity of energy to the battery in a shorter length of time. This implies the purpose of fast charging.

Charge/Discharge and C-Rate

Regarding batteries, 'charge' is the act of accumulating electrical energy within the battery. The battery's cells store chemical energy, which is transformed from electrical energy from an external power source during the charging process. At the same time, ions are usually transferred between the battery's positive and negative electrodes. Conversely, 'discharge' is the procedure of taking the electrical energy that has been stored in the battery and using it to power a system or device. When a battery is discharged, its chemical energy is transformed back into electrical energy, which may be utilised to power a variety of electronics, including computers, phones, and also EVs.

The simplified formula is:

$$Charge/discharge\ Rate = \frac{Battery\ capacity\ (Ah)}{Time\ taken\ to\ charge/discharge\ (hours)}$$

(Ke Bao et al., 2012)

In addition, C-rate is defined as the charge/discharge current divided by the nominally rated battery capacity. If the discharge current is at 1C rate, it means that the battery will be discharged completely one hour.

State of Charge (SOC)

The difference between a battery's current stored energy and its maximum capacity is referred to as the State of Charge (SOC). It is usually written in percentages, as displayed on devices, where 100% represents full charge and 0% represents total depletion. SOC monitoring is essential for controlling battery usage, determining how long a battery will last, and preventing over discharge and overcharging, which can reduce battery longevity and efficiency. Several variables, including as voltage, current, and temperature are combined to determine SOC. To guarantee user convenience and safety, battery management systems (BMS) frequently monitor and display it.

Solid Electrolyte interphase (SEI) layer

The SEI (solid electrolyte interphase) is formed on the anode or cathode surface through the electrochemical reduction of the electrolyte, and it impacts the cyclability of lithium-ion-based batteries. The formation of the passivating SEI layer is pivotal in the development and operation of high-performance batteries. Its function is to inhibit additional electrolyte breakdown, thereby sustaining cycling efficiency. This necessitates strong adherence of the SEI layer to the electrode material, excellent electrical insulation characteristics, and the capacity to conduct lithium ions. Optimizing the quality of the SEI layer on both positive and negative electrode surfaces is also essential for enhancing lithium-ion battery performance, which is due to the impact of variations in thickness on the conductivity of lithium ions across the SEI layer. However, SEI causes problems when it thickens and leads to higher internal resistance of the battery, as well as resulting in a decrease in overall battery capacity. In most cases, SEI layers degrade with repeated cycles of charging and discharging, ultimately resulting in diminished battery performance and reduced capacity retention over time.

AC/DC

Depending on the EV, charging methods may differ – there are two main charging methods alternating current (AC) and direct current (DC). AC is usually used for house supplies and electronics as it is cost-effective. Lower cost encourages customers to utilise more EVs and the governments to equip more AC charging infrastructures. In terms of accessibility, people can use their AC charging at home - the process of installing 120V (Level 1) and 240V (Level 2) may be challenging but costs less than £1000. On the other hand, DC is pricier and seen more commonly in public charging stations, where they have the converters inside it. The major reason drivers would use DC is because it provides much quicker charging compared to AC. The charging time for DC can be up to an order of magnitude faster than AC. Lithium-ion battery fast charging by Anna Tomaszewska et al. (2019) mentions how EV battery packs can be charged with a power of 120kW using Tesla Superchargers and about 350kW through Porsche charging posts. Recently in 2018 in a 'Fast Charge' research project, they have concluded that DC (prototype 450kW) was a big step in increasing power capability throughout the years. This development through the years have been impactful in the field of fast charging systems.

However, since DC also do have limitations, it is critical to acknowledge that DC would not necessarily be the best solution for fast charging, if we consider battery health.

Charging Protocols (CC-CV, Pulse)

Majority of the research papers examine the importance of charging protocols, and the most well-known option is Constant Current - Constant Voltage (CC-CV). Constant Current (CC) is when a source is charged at a constant rate of current, whereas Constant Voltage (CV) is a source being continuously charged at a constant voltage as designated. Since each has its drawbacks, the optimal solution is utilising both, also referred to the CC-

CV option. This allows the charging system to change the CC mode to the CV mode when it reaches a certain output current, ensuring efficient charging without overheating the battery. Some power sources that use CC-CV may incorporate temperature monitoring for safety and minimise overheating concerns. The predominant reason for its wide use is its compatibility: CC-CV applies to batteries that are rechargeable, and therefore can be used specifically for LiFePO4 batteries in vehicles.

The standard charging algorithm of a lithium battery is composed of two distinct operational regions: constant current (CC), until the voltage upper limit is reached; constant voltage (CV), until a SOC level of 100% is reached. The formula is:

$$SOC(k) = \sum_{k=1}^{N} \frac{i(k) * T_i}{dQ(k)/dSOC(k)}$$

where k is defined as the simulation's steps number
N is the number of steps which determines the charging duration
Function dQ is the capacity variation at each step
SOCi is the initial condition of SOC

Ambient Temperature Greatly Influences Battery Health During Fast Charging

Temperature at Which It Is Charged (SEI Layer to Form, Lithium Plating, Other Bad Things) SEI, Lithium Plating, Other Bad

Temperature is an important factor that determines the charging efficiency. However, it has also been found that the effect of fast charging on battery health is particularly sensitive to temperatures. For example, Waldmann et al. (2014) investigated the effect of charging cells at 1C whilst maintaining them at a temperature in the range –20 °C to 70 °C. They found that below 25 °C the primary degradation mechanism was lithium plating but increasing the temperature above this threshold prevented lithium plating. However, this came at the expense of introducing many other deleterious effects such as SEI formation on the anode and degradation of the cathode. As a result, the optimal temperature for fast charging must was found to be around 25 °C, from which it was concluded that internal temperature regulation within the vehicle through heating/cooling systems would be required while more resistant battery technology was developed. This was a seminal study as it showed lower temperatures did not necessarily guarantee less degradation. Beforehand there was a view that only high temperatures had been associated with enhanced battery ageing. Interestingly, Yang and Wang (2018) found that the optimal temperature was more likely to be around 40 °C as the additional positive effect on charge diffusion due to the higher temperature outweighed the negatives.

The Most Significant Internal Factor of Battery: Particle Size Distribution

There are numerous factors that determine the battery performance and fast charging; however, it heavily relies on the modelling of the battery and controlling of the particle size distribution of electrodes. They influence the inner material properties like the reactivity and its electrochemical reactions, and it has been investigated that the nanoscopic, core materials play a crucial role in shaping the efficiency of EVs with LiFePO4 batteries.

Study 1

A paper in 2011 by K. Zaghib et al. (Zaghib et al., 2011) explored the charging of li-ion batteries alongside maintaining safety and a long battery life, which is mainly focused on using LiFePO4 (LFP) in the positive electrode to minimise cost and remain environmentally friendly. It is one of the earliest journals that have investigated the fast charging through a practical (experiment set up).

The paper introduced the significance of 'particle size' which is a parameter that influences the charge transferred while maintaining a certain battery voltage limit, also referring to the rate capacity. Since LFP batteries have been safety tested and have been concluded that its cells are responsible for the long shelf life, the following experiment is conducted. They conducted the experiment using a milling process to produce a range of particle sizes, and concluded that an average size of 25 nm was ideal. Furthermore, the test was carried on with LiFePO4 in a molten state to obtain well crystallised particles. Then carbon was coated onto the particles, in order to increase electronic conductivity. Such factors have all determined the investigation of the performance of batteries when charged and discharged.

They deduced positive results by showing that LFP cells are safe and can support fast charge and discharge rates without any damage for the cycling life. Since electric cars are the most demanding in terms of performance and safety, the impact is significant. In order to accelerate or slow down the vehicle while driving, the fast charge and discharge rates tested in this work are usually required. It also implies that, unlike the traditional battery testing process they have used, the use of a battery in an automobile cannot be replicated by only doing periodic cycles.

Study 2

A more recent paper, in 2016 by Nannan Zhao et al. (Zhao et al., 2016) also reflects how particle size is important in the performance of LiFePO4 cathode material considering a low temperature condition. As the milling time increases, the particle size we obtain decreases. Due to the fact that smaller particles increase surface area and decrease diffusion distance, the experiment similarly uses different ball-milling time (0.5hour, 1hour, 4 hours) to compare the low temperature performance of LiFePO4 materials.

A great consideration was taken by the authors as they have examined the impact of temperature to measure the charge and discharge capacity. Especially, when it comes to electrical vehicles using LiFePO4 batteries, numerous studies over decades have simulated the operation of electric vehicles in cold temperatures. Its results were detrimental when temperature decreased: another 2016 paper (Delos Reyes et al., 2016) concluded that at cold temperatures below around -15°C, it depended on heating or AC, which could be varying for each driver, but for intermediate temperatures had linear models, where average temperature was in the x-axis and travel distance was in the y-axis. (figure 1.1) (Zhao et al., 2016) Adding onto these factors, the 2016 paper touches on the impact of particle size on the electrochemical performance of LiFePO4 batteries. The results were as following:

Table 1. Different samples with different particle sizes

Samples	Particle size (μm)			Specific capacity ($mAhg^{-1}$)		Capacity retention rate (%)
	D_{10}	D_{50}	D_{90}	25 °C	-20°C	
In-LFP0.5	1.10	1.54	1.91	150.7	43.5	28.9
In-LFP1	0.78	1.2	1.63	153.9	52.4	34.0
In-LFP4	0.64	0.98	1.29	158.1	75.6	47.9

Re-LFP0.5	0.95	1.52	2.05	151.3	78.2	51.7
Re-LFP1	0.79	1.12	1.45	154.8	105.6	68.2
Re-LFP4	0.64	1.01	1.35	157.8	112.6	71.4

Conclusion and Need for Further Research

Through the investigations, it is thought to be that all parameters are interlinked with each other, whether it is the macroscopic or the microscopic aspects of charging LiFePO4 batteries. This work summarises the research done over approximately twenty years of the electrical vehicle field from an experiment-oriented perspective and tackles the challenges to consider battery life as well as fast charging. In conclusion, due to limitations with each element, deducing the most efficient method with maximised output is idealistic, however, it is merely impossible. The following is a summary of potential research that may take part in the future to make up for LiFePO4 battery efficiency:

- Balancing each element depending on (difficult to say that one element is more important than the other)
- Actual applications, more investigation on current ev users, how they manage battery efficiency
- More research on simplified mathematical models on sketching the performance of ev, very difficult approach for people to interpret the complicated parameterisations

Some papers such as introduce an innovative framework for managing battery manufacturing systems tailored specifically for EVs. This framework integrates battery operation with manufacturing processes, enabling the prediction of battery life and performance while considering manufacturing specifications and quality control measures. Initially, the paper reviews various modelling approaches for predicting battery performance and examines the rigorous requirements and standards applicable to integrated circuits (ICs) and systems used in battery management. This study also introduces the 'Galvanic Isolation Concept'. The battery system includes the pack management unit. Its role is to acquire data from the module management units and the current sensor, calculate the battery parameters, such as state of charge (SOC), state of health (SOH) and state of function, communicate with the vehicle control system, operate the power switches, and control the battery cooling and heating subsystems. It is necessary to provide a galvanic isolation of the communication lines and the power supply of the monitoring circuits from the rest of the vehicle.

It is especially important to understand this at the cell level of the battery first, both for simplicity during testing and because it is more amenable to modelling. The complication of the full battery is not considered here but is a major complication as many cells packed together in compact geometries will experience different temperatures, with those nearest the centre suffering the highest temperatures and those at the boundaries experiencing the lowest. As a result, the overall state of battery (SOH) of the battery will need to account for the individual SOHs of all the constituent cells. As the review article in 2021 suggested, 'Further studies are needed on how to effectively derate the charging current of lithium-ion batteries to sustain a healthaware fast charging strategy over the cycle life of the battery system.'

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