# ARP research

# Abstract

This article

# Introduction

市场份额及其重要性

Global sales of electric vehicles (EV) have increased dramatically in recent years. Despite experiencing the global covid-19 pandemic last year, sales in 2021 are still up 109% on the previous year, with an absolute figure of 6.5 million. There is 85% of EVs which were sold to the mainland Chinese and European markets. With a series of incentives from the Chinese government, such as subsidies for purchasing electric vehicles and charging subsidies, an increasing number of ordinary users choose electric vehicles as their first choice and alternative for personal mobility, and electric vehicles are playing an increasingly important role in daily life.

制造商

Due to the global trend of energy saving and emission reduction and the dividends in some countries, more and more established car manufacturers with good reputation and emerging car companies are joining in the production and development of EVs, including world giants, BMW, Mercedes-Benz and Audi, emerging manufacturers Tesla, Chinese traditional companies BYD, GAC, BAIC, start-ups NIO, Xiaopeng, etc. they launched distinctive models which satisfies different requirement of consumer segments.

拆解电池的BMS系统

EVs look like a fuel car, but the power is delivered in a very different way. The power battery pack is one of the most critical components and two most important building blocks in a battery pack are the cells for discharging (heart) and the battery management system (BMS) (brain). BMS is a hub for managing and monitoring the power battery, managing, maintaining and monitoring each module of the battery, and shouldering the important task of preventing the battery from overcharging and discharging, prolonging the battery's service life and helping the battery to operate normally. BMS is also an important link between the on-board battery and the electric vehicle. Its main functions include: real-time monitoring of battery physical parameters, battery status estimation, online diagnosis and early warning, charge/discharge and pre-charge control balance management, thermal management and so on. A poor implementation of any of the above functions can be fatal to the battery. The R&D costs for the battery management system account for approximately 20% of the overall battery pack. There are currently three main bodies of the design and production of BMS in the world, battery manufacturers, original equipment manufacturer (OEM) and third parties. Leading Chinese battery manufacturers include CATL, CITIC Guoan and others. Unlike the single battery application in a mobile phone, third parties always have many problems with the BMS development due to their research capabilities because of the intricate charge/discharge relationships and balance within the battery pack, therefore EVs equipped with BMS developed by these companies are sometimes dangerous for these internal defects.

充电烧车的矛盾

Accurate prediction of a series of battery indicators, including state of charge (SOC) (remaining charge of battery), state of health (SOH), state of power (SOP) etc. is one of the important functions of the BMS. Based on the feedback from EV charging companies, it is found that the number of burn-in accidents is particularly high in BMS developed by third parties and some models made by the OEM can also suffer burnouts due to problems with the battery cells. On the one hand, an incorrect estimation of the remaining charge by the BMS leads to the BMS continuing to send charging demands to the charging piles, while the charging platform, after parsing the vehicle-side message, gives instructions to the charging piles to continue charging. The voltage, current, internal resistance, temperature and other data recorded in the message at this point are all normal. However, the battery is already showing signs of overcharging in reality. As the internal chemistry of the battery is very sensitive to temperature, the significant increase in charging temperature due to overcharging usually occurs at the end of charging and is therefore ignored by the BMS, at which point the situation is no longer controllable. On the other hand, Even if BMS is correct in its prediction of SOC, the characteristic of low ignition point in cells may lead to fires, such a problem is easier to solve technically, for example, wrapping the cells in a flame-retardant material.

充电企业的困境

In the accident of burnout, as EV charging companies, they may have to carry more public pressure, as consumers at one charging station will instinctively assume that there is a problem with the station's charging piles, while their usual driving and other charging behaviours are unaffected. Internally they do not know how to improve their own charging piles, as the piles themselves only receive the data sent by the BMS to make the next judgement, and the BMS itself has the incorrect data. For such a dilemma, the only thing that can be done at the moment is to rank the effectiveness of BMS designed by different manufacturers and to take charging restrictions for models that are highly prone to problems. This is a mechanical selection, just as the corpus is subject to a strong time constraint for updating. In order to improve the performance of BMS and make the prediction more precise, it is necessary to increase the computational power by adding chips and embed some flexible models which are apply the principle of machine learning.

文章的map

This paper will analyse why Li-ion batteries are suitable as battery packs for EVs based on the physicochemical properties of lithium batteries and some mature theory and practice already in place in the literature review. In the models and methodology part, the fundamental principles of methods will be introduced. How the remaining battery charge can be more accurately predicted (comparison of some models based on the properties of Li-ion battery charging and discharging). Conclusions will be drawn in the modelling phase using publicly available EV laboratory data. In the final section, the deployment of those models is also worth discussing.

# Literature review

## The charging and discharging mechanism of Li-ion batteries

锂电池充放电的机制

The interior of a Li-ion battery has three components, anode (negative electrode) and cathode (positive electrode) and electrolyte. Anode and cathode are separated by a separator and the electrolyte fills the interior of the battery (Zhong et al., 2015). The materials used in Li-ion batteries are very elaborate. Firstly, cathode material is lithium salt. There are three main types of lithium salt used as cathode material, namely lithium cobaltite (LiCoO2), lithium iron phosphate (LiFePO4) and ternary lithium. Lithium cobaltite is the most expensive to synthesise and is therefore not used in large numbers in EVs, but it also has the highest output voltage. Lithium iron phosphate is less expensive and has the highest number of available charges and discharges, allowing it to be used in EVs, but its output voltage is the lowest. Tritium combines the advantages of these two types of Li-ion batteries, using a manganese (Mn) nickel (Ni) iron (Fe) mixture as the anionic part of the lithium salt ().

Anode material is graphite or coke because its laminar structure can hold Li-ions. Electrolytes are liquid and consist mainly of inorganic solutes and organic solutions. The inorganic solute is mainly lithium hex phosphate fluoride (LiPF6), while the organic solute is Ethylene Carbonate (EC, highly conductive but viscous) and Dimethyl Carbonate (DMC, weakly conductive but less viscous), exactly two materials to compensate for their respective physicochemical deficiencies (Zhang, 2018).

The charge/discharge chemistry of a Li-ion battery is a regular movement of Li-ions between anode and cathode. Then, take LiCoO2 as an example, LixC6 (compounds for anode) breaks down into Li-ions (Li+), electrons and carbon ions (C-) during charging. The separator only allows Li+ to pass through but not electrons, so electrons are transferred from the external circuit to cathode, and Li+ move towards the cathode due to the electric field created by the external electron movement, reaching the cathode through the small zigzagging hole inside the separator, where they combine with electrons and cobaltite ions (remains in the anode) (CoO2-) to produce lithium cobaltite, while other ions left in the anode combine with the cations in the electrolyte to form compounds (Roy and Srivastava, 2015). On the contrary, when discharging, lithium cobaltite in the cathode decomposes to Li+, electron and CoO2-, electron still moves from external circuit to anode, and at there, it combines Li+ and CoO2- as lithium cobaltite (Belov and Yang, 2007a).

SEI膜的介绍以及在各种情形下锂电池为什么会老化的机理

## The aging mechanism of Li-ion battery

After the battery has been assembled, at low temperatures, the Li-ions on the surface of the two electrodes react with the electrolyte to form a solid electrolyte interphase (SEI), which has both positive and negative aspects. It prevents the electrolyte and Li-ions from continuing to react and blocks electrons and bulky solvent molecules from entering the electrodes. However, in order to create it, some of the Li-ions are consumed and the active Li-ions are reduced. Most of the causes of ageing are related to SEI, the following is scenarios.

1. Charging and staying in high temperature (only exceeding 60 degree celsius): High temperatures lead to the dissolution of the SEI, making it no longer able to isolate the electrolyte from the Li-ion. Electrolytes such as LiPF6 and EC are decomposing at high temperatures, and the products of decomposition react with graphite to change their layer structure, thus reducing the space left for Li-ions (Sarre, Blanchard and Broussely, 2004).
2. Charging in low temperature: The low temperature makes the lithium monolith precipitate, the Li-ions gather on the SEI without passing, get electrons to form lithium atoms stacked on the SEI, over time the lithium atoms deposit and break through the SEI, forming a tree-like lithium dendrite (). The continuous generation of lithium dendrites may puncture the separator (Zhang, Xu and Jow, 2003).
3. Over-current: On the one hand, the thermal effect of the current makes the electrolyte decompose. On the one hand there is an excess of active Li-ions, which leads to saturation of the electrode material and the formation of lithium dendrites from the excess Li-ions. In addition, the resistance of the SEI becomes smaller at higher currents, allowing electrons to pass through and the Li-ions to precipitate directly on the electrode surface before they can diffuse (Belov and Yang, 2007b).
4. Self-discharge: Self-discharge is more likely to occur in winter and summer, at higher and lower temperatures.
5. Aging of battery module: The ageing of single cells leads to an amplification of the ageing of the modules. At the same time, the joints between the individual cells are also being oxidised and ageing, which deepens the ageing of the modules (Ping et al., 2018).

前后状态的相互关联是有理论依据的

In summary, the liquid electrolyte Li-ion battery is fragile and its internal chemistry is extremely sensitive to current, voltage and temperature. Improper usage leads to accelerated ageing of Li-ion batteries. Currently, the use of solid electrolytes instead of liquid is the industry's direction of development. However, the chemical reaction is a step-by-step process, so if the remaining charge in the last state of the battery is accurate, it indicates that the state of the electrodes, the concentration of active Li-ions, and the state of the SEI at the previous moment are accurate, there is, therefore, a theoretical basis for predicting the next state of power based on the previous state's power adjust some parameters that change internally.

## State of Charge and State of Health

The descriptive formula for battery capacity after removal of loss current is:

If the current is constant during full charging and discharging, the time is the total time required to complete the process, if the current is not constant, the equation is written in integral form:

The percentage of battery capacity to rated capacitance is the state of charge:

If letting time to be infinite small, instantaneous SOC will be obtained. Ampere-hour method is using the initial SOC derived from the correspondence between open circuit voltage and SOC at a fixed temperature to minus the current SOC.

State of health measures the effect of the internal resistance of the battery on charging and discharging. The higher the internal resistance, the more times the battery has been charged and discharged, the fewer times it is available, and the more the battery ages.

## SOC prediction methods

电池预测的方法，三大类，电化学模型，等效电路模型，神经网络模型

电化学

There are currently three ways to consider the prediction of SOC. The first approach is to construct a series of mutually coupled partial differential equations to describe in detail the changes in Li-ion concentration, the changes in electrode potential and the quantification of the polarisation reaction during the charging and discharging of the battery. This method is the most accurate way, but more difficult to apply in practice because it is difficult to formulate the equations and even more difficult to solve them.

神经网络

The second approach is to use neural networks, built on a large number of HPPC tests on a single type of battery (e.g. lithium iron phosphate as cathode material), to obtain experimental data on the internal resistance of the battery charge and discharge, and the electrical power. In order to make the model more accurate, some modifications need to be made to the fully connected layer to take into account the influence of the SOC of the previous state of the battery on the current SOC prediction, so recurrent neural networks or long and short-term memory are introduced for relationship fitting. This method can be used to obtain relatively reliable prediction curves directly without considering any internal battery chemistry mechanism.

The problem with this approach, however, is firstly the demanding data quality and volume of data required for the training set, and secondly the poor generalisation capability of the model, and the fact that if the cathode material is replaced with another lithium salt, such as ternary lithium, the existing relationship may change.

等效电路

Using an equivalent circuit model, the inherent internal resistance within the lithium battery due to the electrode material and electrolyte chemistry is equated to the ohmic internal resistance, the internal resistance formed after the polarisation reaction is equated to the polarised internal resistance, the electrical capacity of the lithium battery is equated to the capacitance, which is connected in parallel with the polarised internal resistance, and whether or not an external power supply is used is equated to a charge/discharge simulation of the lithium battery, thus forming an equivalent circuit. Battery terminal voltage, current, electrical power and other parameters can be replaced by testing the equivalent circuit data, by studying the change in the value of each resistance within the equivalent circuit to simulate the internal electrode potential change of the lithium battery, so as to obtain the prediction of SOC and SOH.

As an observed value, open-circuit voltage is usually regarded as the actual terminal voltage of a Li-ion battery. The measurement requires the battery to be left to stand for a long time after charging or discharging in order to stabilise the polarisation and thermal reactions within the battery. In the HPPC test, each short charge and discharge is followed by a 1 hour rest period in order to observe that the open circuit voltage is more in line with the actual terminal voltage (Rezvanizaniani et al., 2014) (Stern & Geaby, 1957).

Based on the definition of SOC, second method, ampere-hour integration method uses the initial capacity of the battery minus the capacity of the battery that has been discharged. Due to the instability of the current, the equation is often expressed as an integration form (Li et al., 2019).

SOC(t0) refers to the remaining charge of the battery at the moment t0, Crated refers to the rated capacitance, and Ib-Iloss refers to the actual current after taking the loss. The formula describes the remaining power equal to the area of SOC in the initial state minus the area of power consumed in actual use. This is in some ways the most accurate and straightforward method, but it is dramatically influenced by three variables. One is the SOC(t0), which is also difficult to measure, and it is debatable whether the remaining battery capacity measured before each start with the battery can be accurately used as the next time’s SOC(t0). Second is Crated. The rated capacitance of the battery also varies each time it is used, due to problems such as battery ageing (CSDN, 2021). Thirdly, the biggest problem with integration is that if the current is not measured correctly or the time interval between measurements is too long, then this problem will be magnified and will be far from the real battery capacity (Hua & Li, 2013).

Perhaps SOC of the current period are not unrelated to SOC of the former period, and this is why third method emerges. This method is the modification of ampere-hour method by using Kalman Filter (KF), which have effective result in the noisy environment. Pang, et.al (2020) considered Kalman filter and weighted the current of former period and current of latter period to figure the modified SOC in current period. Furthermore, even if the whole battery system is in an unstable state or there is some noise on the data, Kalman filter enables the determinant of the uncertainty matrix of the system to be continuously reduced so that the observed and predicted values tend to be equal and only the error between the real value and the observed value is retained (Kalman, 1960). The Extended Kalman Filter (EKF) improves on the original linear relationship by introducing a non-linear function and calculating the partial derivative of the non-linear function, which is more accurate than the KF because it is not yet clear how the SOC changes (Pang et al., 2021).

The last method is to use artificial neural network to analyse the inner patterns of data. Although this is a most costly method compared with other three, it is more accurate than other at the same time. Considering that there is continuity between SOCs and that the current SOC may be correlated with previous or even next periods, recurrent neural networks are introduced (Han, 2017a). The standard recurrent neural network gives the maximum weight to the SOC value of the most recent previous period, and the further away from the current period, the less weight is assigned. This is both an advantage and a disadvantage. Long and short-term memory will first assign weights to the first n periods, find some of the first n periods that most affect the current period and assign larger weights, and vice versa, assign smaller weights (Han, 2017b). Deep neural networks require a large amount of data for training, and there is no good automatic solution for tuning the various hyperparameters, which needs to be set manually.

# models AND METHODOLOGY

## Design of equivalent circuit model

锂电池的电化学模型先放一放，这个比较难理解，优先选择等效模型，然后是nn，再是电化学模型

验证二阶RC电路可以比较有效的等同于锂电池充放电过程

为什么要使用二阶等效电路，把那个人的论文概括一下

In fact, there are better electrochemical models for the determination of the internal mechanism of lithium batteries, such as the Shepherd model and the Unnewehr unified model. However, in order to facilitate their use in practical scenarios and to describe their mathematical relationships more easily, the complex electrochemical models were transformed into battery electrical models, in which the equivalent circuit model can better simulate the charging and discharging of the battery. The basic component unit (RC model), consisting of a capacitor and a resistor in parallel, simulates one electrode of the lithium battery and simulates the polarisation reactions that all occur during use. Lithium batteries have two electrodes and therefore two such components are connected in series within the single circuit. In addition, the inherent internal resistance of the system (ohmic internal resistance) is generated by the chemical properties of the battery's electrolyte, electrode material, etc., and is also taken into account by connecting them in series.

图示

描述已自动生成

Uoc is the open-circuit voltage of the battery, which is a function of the value of SOC at constant temperature, R0 is the ohmic internal resistance, R1 and R2 are polarised internal resistances, C1 and C2 is the polarisation capacitance. The decay of the voltage across the capacitor has an exponential relationship with time.

The relationship can be expressed as:

Change in voltage at the capacitor terminals during charging:

设计一个HPPC实验，然后用bamm画出图，列出公式

The HPPC experiment can be designed and some critical parameters will be confirmed, using a battery-related package called Pybamm to do the mock experiment.

HPPC experiment plan:

HPPC result:

According to the end voltage decay equation, the decay is more pronounced when time is varied over a smaller range, but as time passes the voltage decay approaches 0. At this point the capacitor end voltage is nearly equal to the open circuit voltage and the OCV is measured more accurately. This is why long standing times are required in HPPC experiments.

Voltage of this equivalent circuit with zero input response:

when this system is in discharging state

The voltage at zero state response consists of three parts, one is the voltage consumed by the ohmic internal resistance, one is the attenuation of the residual voltage inside the capacitor and one is the superposition with the zero input response.

Total voltage in the discharging scenario

## Kalman Filter and its expansion

The basic idea of Kalman filtering holds the view that the observed value obtained from experiment and the predicted value obtained by the inner pattern are both inaccurate, in order to obtain a more accurate estimate, it is necessary to weight these two values, the current state of a system is from weighted calculation between these two values from the former states, which is so called dynamic update. After several steps, the difference between the obtained estimate and the true value will decrease dramatically. Assuming the relationship between the observed and true values, the relationship between the predicted and true values are in accordance with the Gaussian distribution, the position with the highest probability in the distribution represents the true value, and the standard variance of the observed value’s distribution is significantly smaller than that in predicted value’s distribution, which is reflected in the weight assignment, and the observed value gets a larger weight.

Suppose the true value of each state of a linear system is xk, then the state equation of the system can be written with a control matrix and the previous period jointly determined by the equation, the control matrix determines what law the whole system will follow, for example, in a system of uniformly accelerated linear motion, the displacement of the object s =1/2\*vt^2, in a battery system, the control matrix means that the capacitance of the battery after time t:

A denotes a state transfer matrix, B denotes a control matrix, u denotes the control vector, and w denotes the noise present in the real system, this equation shows that the estimate in period k depends on the estimate in the previous period, the control situation provided by the previous period to the next period and the system noise.

The observed value can be measured by the instrument, based on the measured value, the transformation matrix can be calculated from the following equation:

For the predicted value, this logic is consistent with the true value, which can be obtained from the predicted value of the previous period and the control vector, the noise could be taken into consideration in this equation.

Therefore, estimated value is generated by the weighted calculation from observed value and predicted value:

Kalman gain matrix is introduced to redefine the calculation of the estimated values:

The cleverness of this equation is that the relationship between the predicted and observed values is portrayed by a Kalman gain matrix that iterates over time. represents the residuals between predicted value and estimated value, which could be large at the beginning of the system state. A large residual indicates that there is a large gap between the true and predicted values . When the system is updated after several steps, the residual decreases, the gap between the predicted and estimated values decreases, and the influence of the observed values is gradually reduced. At this point, the predicted values inferred from the internal laws of the system can already better reflect the true value and observed value.

To determine several variables mentioned above, the covariance matrix is introduced for matrix transformation. Assuming the presence of noise matrix Q of the system operation in the current period and the true value of the previous period, the presence of observation noise matrix R in the observations, the covariance matrix between the predicted and true values is (residual value), and the covariance matrix between the estimated value and true values is (remaining value).

All the matrix will be updated as follows:

Step parameter is k=1, the initial estimated value is , the initial covariance matrix is . the process of algorithm is described as follow:

For (int k = 1; k <= step.length; k++) {

update the predicted value

update covariance matrix between predicted value and true value (state covariance matrix)

update Kalman gain matrix

update estimated value

update covariance matrix between estimated value and predicted value

}

if the predicted and estimated values after each cycle are stored separately and displayed as images, it can be seen that the estimated and predicted values are getting closer and closer after the cycle.

Based on the state and observation equations within the linear Kalman filter model, the equations on SOC prediction can be established:

In this system of equations, the control matrix is the ratio of the accumulated capacitance to the rated capacitance at the capacitor charging and discharging efficiency η, in other word, the descriptive formula for capacitance, where the ampere-time integration method is used as the calculation of SOC. The observation matrix H is the residual voltage obtained by removing the second-order equivalent circuit, the battery internal resistance, and the voltage consumed by the two polarized internal resistances from the open-circuit voltage. and represent two noise from system operation and observation noise.

According to the formula of voltage decay and time, and can be obtained:

Therefore, it can be found that under the second-order equivalent circuit method, the Kalman linear equation is a function with respect to the natural base (e), and this equation is no longer linear, so mathematically, the exponential function is approximated by the Taylor series formula.

However, according the equivalent circuit method from above, the voltage calculation method is abstracted to obtain the fact that the SOC conforms to the double exponential model:

## Neural network

Putting aside complex circuit and electrochemical models for the moment, it is simple and brutal to create a dataset and drop it into a neural network model, which acts as a black box to help find the best fit function to solve the relationship between SOC and OCV