Chapter 5

Batteries for EVs and their parameter estimation

5.1. Introduction

The transition to sustainable mobility and transport electrification has become almost necessary to reverse the rapid occurrence of climate change and global warming. Replacing fuel-based automobiles with electric vehicles is a change that requires research and development of more efficient and long-lasting electric battery sources. A battery source is an essential component in electric vehicles, since its effective utilisation leads to enhanced battery longevity. Battery research has progressed at quite a rapid pace, and most portable applications today can be satisfied by batteries. However, improvements are definitely needed if this power source is to be extensively used for electric vehicles (EVs). The evaluation of vehicle performance relies significantly on essential parameters that include the energy storage capacity of batteries, their state of charge and efficiency. A considerable portion of the cost and environmental impact of an electric vehicle are attributable to the battery. Electric vehicle batteries are energy accumulators that supply electricity to motors for vehicle transmission. They are more significant in that the use of batteries will make cars more durable and free them from the need for fossil fuels. Personal mobility is an issue that cannot be suppressed, even if it tends to affect the environment in a negative way [1]. Though the battery world has experienced an unprecedented revolution in the last decade, the search for the perfect super battery is therefore a crucial issue. This chapter discusses batteries used in EVs and battery technology in general. Battery modelling, along with its different existing approaches, has been studied, and a simple electrical circuit battery model has been simulated, which allows analysis of battery behaviour. Additionally, this study proposes a motor-generator-linked automated technique for the estimation of battery-related parameters, which plays a key part in the implementation of eco-routing strategies for electric vehicles. The Arduino-MATLAB platform has been utilised for all simulation and post-processing operations. This system helps in the extraction of important battery parameters, which in turn are used in the energy consumption estimation of electric vehicles.

The battery serves as the principal energy provider in electric vehicles. Batteries play an essential role in mitigating greenhouse gas emissions by effectively storing electricity derived from both conventional and renewable energy sources, while also serving as a reliable power supply for electric automobiles. Renewable energy sources have become crucial in ensuring a consistent and sustainable power supply, hence playing a pivotal role in the complete implementation of renewable energy technologies. In an EV, the battery serves as the primary power source for all system operations, including the propulsion motors. According to reports, the lack of precise range information continues to impede the widespread adoption of EVs. Consequently, there is a need to emphasize on enhancing battery energy capacity in EV technology [2]. Many EVs are still perceived as facing challenges related to limited driving range and expensive battery technology [3]. The research work is mainly focused on energy-efficient navigation systems, which demand effective usage of the battery in use. Eco-routing navigation is a relatively new concept in the realm of vehicular technology. These systems can be used to save energy by predicting energy-efficient routes, which in turn makes the determination of battery parameters quite crucial. Since saving as much energy as possible is currently of paramount importance, eco-routing can prove to be a sustainable solution in mobility model designs. The use of mobility models based on the eco-routing concept can help extend the range and improve the energy efficiency of electric vehicles [4]. The life of a battery is directly proportional to its capacity. It is mostly determined by the amount of energy that is being consumed by the device. Optimised usage aids in the lengthening of battery life. The viability of the electric mobility system is heavily influenced by the driving range performance of EV batteries, as stated by experts [5]. This work mainly involves lead-acid batteries. Its merits in EV technology have been discussed. The efficiency of this battery type generally ranges from 70 to 90 percent [6]. This type is perfect for automobiles like neighbourhood electric vehicles (NEVs), which aim at providing affordable and efficient transportation, but their speed and range issues are not major concerns [6].

Batteries exhibit non-linear characteristics, which complicate the prediction of vital parameters like efficiency and state-of-charge (SoC). The determination of battery parameters is quite crucial for eco-routing navigation as well as range estimation for an EV. Battery technology is currently a highly researched field and is mainly aimed at increasing capacity and efficiency and also finding greener and more sustainable substitutes for the preservation of the ecosystem. Although extensive research has been presented in the literature, a universal procedure for the determination of battery parameters like the State-of Charge in a battery has not yet been reported. Researchers use a variety of battery models to simulate the performance of vehicles using battery sources. Electric vehicles are an area in which batteries play an essential role. EVs cannot function without a power source. They serve a pivotal role in terms of sustainable mobility. In recent times, there has been a notable surge in the use of EVs for both personal transportation as well as cargo. There is a prevailing projection that EVs will imminently supplant conventional fuel-powered automobiles. The aforementioned progression has numerous ramifications for the tank-to-wheel process [7]. Newer technologies like Waves-to-wheels for port areas are also being researched [8]. So, an estimation of battery parameters is necessary for choosing the battery appropriate for that particular vehicle. Parameters like SOC and Coulombic efficiency are required in the calculation of the range of the EV. They are also required for EV-based applications like eco-routing navigation, where energy minimisation is concerned. As previously stated, eco-routing navigation systems appear to be a viable means of establishing sustainable mobility paradigms. This concept is based on the principle that individuals minimise their generalised travel costs, which are primarily operationalized through a combination of travel costs and travel time [9]. In most cases, the battery parameters are determined automatically using market-available equipment. However, they are expensive and, at times, difficult to utilise for students or researchers. Literature suggests that there are not many techniques and setups proposed for this type of work. Sharma et al. published a method for evaluating the coulombic efficiency of lead acid batteries in 2015 [10]. The limitation of that approach is that the rate of discharge or charge cannot be fixed or measured by that method, making accurate parameter determination impossible. The technique proposed here is a simple, user-friendly, and cost-effective method for the evaluation and analysis of battery parameters. It consists of a motor-generator-coupled technique for recording the charging and discharging cycles of batteries. Lead-acid batteries have been used for the experimentation. A highlight of this technique is that the proposed method and set-up can be used to test any type of battery, like lithium-ion batteries and other energy storage systems, and determine the consequent battery parameters. It is portable, has high repeatability, and can thus be utilised by anyone, whether for research or industry. Compared to commercially available devices, this technique is straightforward, and the setup is basic and straightforward. It is particularly cost-effective due to the use of simple and readily available components in the circuitry. Since the system has been built in quite a transparent way, it is easy for all to understand the working principles. This configuration aids in obtaining real-time results, allowing the current to be estimated at any instant. The detection of battery metrics such as efficiency is an important feature of any battery-based application, particularly those based on electric vehicles. These parameters are necessary for determining range and estimating energy usage in electric vehicles.

5.1.1. Basics of electric vehicle battery

A battery source is comprised of a series or parallel arrangement of two or more electric cells. The chemical energy contained within cellular structures undergoes electrochemical reactions in order to be transformed into electrical energy. A cell is formed by connecting a set of positive and negative electrodes through an electrolyte [11]. The creation of direct current, which finds application in numerous battery systems, is attributed to the chemical interaction occurring between the electrodes and the electrolyte. In the context of secondary or rechargeable batteries, it is possible to reverse the chemical reaction by altering the direction of the electric current, so restoring the battery to a charged condition. The electric vehicle battery is a distinct variety of rechargeable battery that is specifically designed for the purpose of supplying power to the electric motors of an electric vehicle [11]. They are meant for the traction of the motors and are also called traction motors. EV batteries have many characteristics that make their use in EVs almost indispensable. The weight of the battery is a prime feature. Lightweight batteries are preferred for vehicles because the reduction in the overall weight of the vehicle improves its performance. The greater the density, the greater the storage capacity, and the longer the EV range [12]. The power that the battery can supply is another important characteristic. More power results in improved vehicle performance. The driving pattern also influences battery life. EVs have longer lives when driven on urban roads. It is seen that most current battery technologies have specific energy on the lower side, which often impacts the maximum range of all-electric vehicles. It is therefore an area that requires research and development.

5.1.2. Types of battery used in EVs

Electric vehicles utilise batteries as a means of storing energy within its energy storage system. The battery type employed is contingent upon the specific classification of the vehicle in which it is being utilised. Batteries serve as the primary source of power for both all-electric vehicles (AEVs) and plug-in hybrid electric vehicles (PHEVs). Certain types of batteries have the capacity to endure for a period of 12 to 15 years under moderate climatic conditions, but in more severe climates, their lifespan may range from 8 to 12 years [13]. There exist multiple battery types for EV-based applications, including Lead-acid, Nickel-Metal-Hydride (NiMH), zinc-air, and Lithium-ion (Li-ion), among other variants.

a. **Lead Acid**

The lead-acid battery is widely recognised and extensively used as the most prominent battery type in the automotive industry. The invention of the battery is credited to Gaston Planté in the year 1859. While the fundamental components of the battery have undergone substantial changes over the course of history [14], its overall design has stayed mostly unchanged. The utilisation of this particular battery variant is prevalent in traditional automobiles, mostly for the purposes of initiating the engine, facilitating ignition, and providing illumination (often referred to as starting, ignition, and lighting, or SLI). Additionally, it may serve a limited number of supplementary electrical duties. Deep-cycle lead-acid batteries are employed in EVs due to their capacity to sustainably meet the power demands. Lead-acid batteries are classified as wet-cell batteries and possess a nominal cell voltage of 2.1 volts. The positive active material used in this context is characterised by a high degree of porosity, consisting of lead dioxide. Conversely, the negative active material employed is composed of finely divided lead particles. The electrolyte used is a dilute aqueous solution of sulfuric acid, which actively participates in the discharge process [14]. This concept is effectively depicted in Figure 5.1. In the case of EVs, a gel electrolyte is employed instead of a liquid electrolyte, hence enhancing the durability of the system. Despite exhibiting a notably low energy-to-weight ratio and energy-to-volume ratio, the cells possess a very substantial power-to-weight ratio due to their capacity to provide significant surge currents. The aforementioned characteristics, in conjunction with their affordability, render them appealing for implementation in motor vehicles as a means of supplying the substantial electrical current necessary for automobile starter motors. The primary disadvantages associated with this particular type include battery construction, which exhibits an obvious weight, as well as its limited range for EV applications, hence contributing to concerns regarding range anxiety. Table 5.1 presents a summary of the nominal battery parameters pertaining to lead acid batteries. The electromechanical reactions that take place throughout the charging and discharging operations can be described as follows:

$$Pb_{O_2} + Pb + 2_{H_2}S_{O_4} \xleftrightarrow{charge\ \_discharge} 2PbS_{O_4} + 2_{H_2}O \tag{1}$$

Table 5. 1 Nominal battery parameters for lead acid batteries

Specific energy	35- 42 Wh.kg^{-1}(depending on usage)
Energy density	54–95Wh.L^{-1}
Specific power	~180 - 250 W.kg^{-1}
Nominal cell voltage	2.1V
Internal resistance	Extremely low, ~0.022 Ω
Operating temperature	Ambient
Self-discharge	~2% per day
Number of life cycles	Up to 800 to 80% capacity

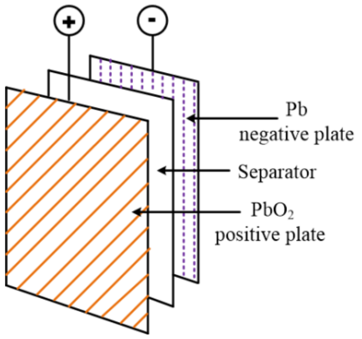

Fig.5. 1 The chemical structure of a lead acid battery cell

b. Nickel-Metal-Hydride (NiMH)

NiMH batteries are considered to be a prominent battery type utilised in EVs . Their use in hybrid electric vehicles is prevalent owing to their superior energy storage capacity in comparison to lead-acid batteries, much longer lifespan, as well as reduced weight [15]. The chemical process occurring at the anode involves the use of nickel oxide hydroxide (NiOOH). Instead of traditional cadmium, the negative electrodes employ a hydrogen-absorbing alloy. Figure 5.2 illustrates the electrochemical reactions occurring within a Nickel Metal Hydride (NiMH) battery. According to research findings, a NiMH battery has the potential to possess a capacity that is two to three times greater than a nickel cadmium (NiCd) battery of the same size. Furthermore, the energy density of a NiMH battery has the capability to reach levels comparable to that of a lithium-ion battery [15]. A HEV is equipped with either an internal combustion engine or electric motors as the primary power source for propulsion. The self-discharge rate of this battery is elevated, and it possesses the ability to provide quick power bursts. Nevertheless, the longevity of the battery will be diminished when it undergoes recurrent instances of quick discharges accompanied with substantial power demands, which are intended to provide a rapid surge of energy. Hence, this particular battery variant is deemed more appropriate for HEV implementations as opposed to BEVs, as the latter generally experience more frequent and intense discharge cycles. The nominal battery specifications for a NiMH battery are presented in Table 5.2. The electromechanical reaction for the charging and discharging procedures of this battery can be represented by the following equation.

$$MH + NiOOH \xleftrightarrow{charge-discharge} M + Ni(OH)_2 \tag{2}$$

Table 5. 2 Nominal battery parameters for NiMH batteries

Specific energy	60-120 $Wh.kg^{-1}$
Energy density	140-300 $Wh.L^{-1}$
Specific power	250-1000 $W.kg^{-1}$
Nominal cell voltage	1.2V
Internal resistance	Low
Operating temperature	Ambient
Self-discharge	High. 13.9-70.6% at room temperature
Number of life cycles	180-2000 cycles

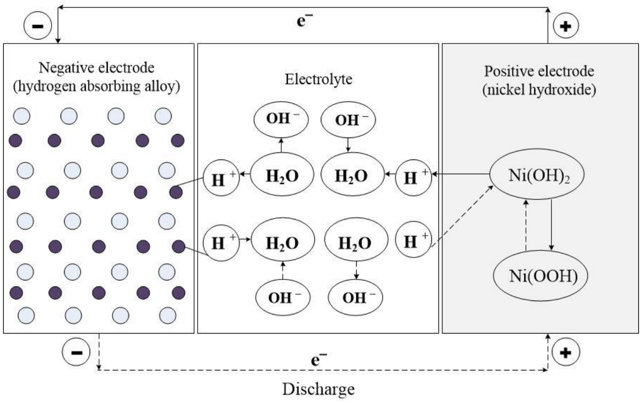

Fig.5.2 A schematic of the NiMH battery cell.

c. Zinc air

The zinc air battery has certain similarities to the aluminium air battery, although it surpasses the latter in terms of overall performance, particularly in specific power. The zinc air battery boasts a specific power that is approximately 10 times more than that of the aluminium air battery, rendering it a viable option for integration into road vehicles. The configuration exhibits a comparable arrangement, featuring a permeable positive electrode where the process of oxygen interaction with the electrolyte occurs. The electrolyte is a solution with alkaline properties. The solid zinc serves as the negative electrode. The energy derived from the battery is acquired by the process of mixing zinc with atmospheric oxygen, resulting in the formation of zinc oxide [16]. Figure 5.3 illustrates the chemical reactions that take place within a cellular environment. In certain circumstances, the formation of zinc hydroxide, similar to the process observed in the aluminium-air cell, may occur based on the condition of the electrodes and electrolyte. Typically, the process exhibits irreversibility. The overall attributes of the battery has also been discussed. Several manufacturing firms have made assertions on the production of electrically rechargeable zinc-air batteries; however, the number of cycles achieved in practise is typically limited. The conventional method of recharging is analogous to that of the aluminium air cell, involving the replacement of negative electrodes. Table 5.3 presents the nominal battery parameters.

Table 5. 3 Nominal battery parameters for zinc air batteries

Specific energy	230Wh.kg^{-1}(depending on usage)
Energy density	270 Wh.L^{-1}
Specific power	105 W.kg^{-1}
Nominal cell voltage	1.65V
Internal resistance	Medium
Operating temperature	Ambient
Self-discharge	High
Number of life cycles	>2000

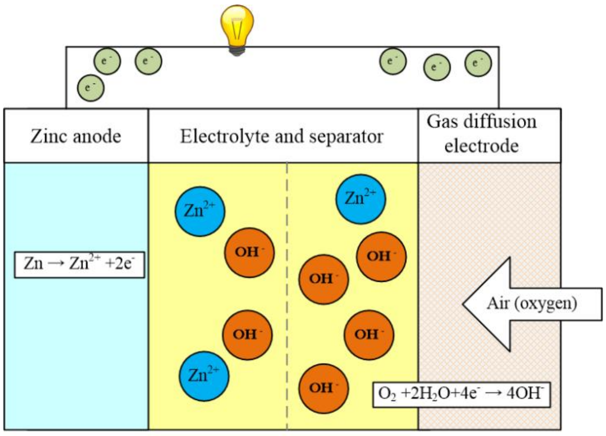

Fig.5.3 General working of a zinc air battery

d. **Lithium Ion (Li-ion)**

The lithium-ion battery is one of the primary batteries employed in EV technologies [17]. The superiority of this particular battery over nickel chemistry can be attributed to a variety of aspects, including as its higher energy capacity in a significantly lighter form, minimal self-discharge, and favourable temperature characteristics. The utilisation of a lithiated transition metal intercalation oxide for the positive electrode and lithiated carbon for the negative electrode was first introduced during the early 1990s [18]. Non-aqueous electrolytes are employed in Li-ion batteries due to the highly reactive nature of lithium when exposed to water. The separators employed in this context typically consist of microporous plastic sheets, which can be optionally treated with ceramic particles to augment the safety features of the cells. One notable advantage of utilising Li-ion batteries lies in their environmentally conscious attributes, as the majority of their constituent components can be effectively recycled. The battery incurs a greater cost relative to other battery types due to its numerous advantageous attributes. However, lithium-ion (Li-ion) batteries continue to be the favoured option for the majority of hybrid and battery-electric cars [18]. The use of lithium-ion batteries in electric vehicles is fostering additional investigation and facilitating a reduction in expenses. The comprehensive electromechanical process of charging and discharging this battery is regulated by the following equation:

$$Li_{t-x}CoO_2 + C_nLi_x \overset{discharge-charge}{\Longleftrightarrow} LiCoO_2 + C_n \qquad (3)$$

Table 5.4 presents some essential characteristics of the Li-ion battery. Precise regulation of voltage is crucial in the process of charging lithium cells. If the voltage level exceeds the recommended threshold, it has the potential to cause harm to the battery. Conversely, if the voltage level falls below the optimal range, the battery will not receive an adequate charge. Figure 5.4 depicts the overall operational mechanisms and electrochemical processes occurring within a lithium-ion battery cell.Table 5.4 presents several essential characteristics of the Li-ion battery. The schematic representation of the operational mechanisms and electrochemical processes occurring within a lithium-ion battery cell are depicted in Figure 5.4.

Table 5. 4 Nominal battery parameters for lithium ion batteries

Specific energy	100-265 Wh.kg^{-1}(depending on usage)
Energy density	250-693 Wh.L^{-1}
Specific power	~250-300 W.kg^{-1}
Nominal cell voltage	3.5V
Internal resistance	Very low

Operating temperature	Ambient
Self-discharge	~2% per month
Number of life cycles	>1000

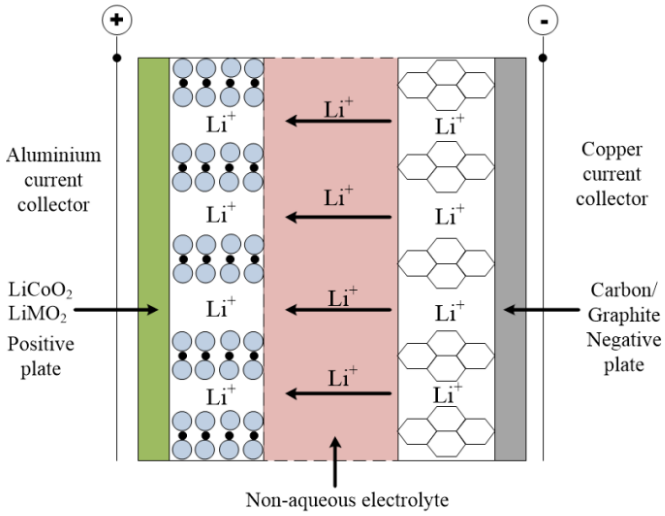

Fig.5. 4 Schematic of a lithium ion battery

5.1.3. *Importance of lead acid batteries in automotive industry*

Lead-acid batteries were the most popular option for EV power sources in the past. EV1 and other early modern electric vehicles were powered by these batteries. These batteries have much lower specific energy than fossil fuels, making them a more environmentally friendly power source. Even though its usage has decreased over the years as a result of newer technologies, it is still the most widely used battery technology in research. Most of this research also involves experiments with rechargeable lead-acid batteries. Two main types of lead acid batteries are engine starter batteries and deep cycle batteries. Numerous EVs favour deep cycle batteries due to their ability to supply continuous energy [18]. They can also be used as a reserve power source in vehicles, though special charging procedures are required. The majority of EVs previously utilised lead-acid batteries because they were inexpensive, readily available, and technologically well-established. In addition, the charging and discharging of lead acid batteries resulted in the release of gases that were harmless if adequately vented. This provided EV drivers with peace of mind regarding pollution's impact on the environment. Deep-cycle lead batteries are expensive and have a shorter lifespan than the vehicle itself, necessitating replacement approximately every three years. The excessive weight of these batteries was one of their disadvantages. 25–50% of the EV's mass was accounted for by the battery weight alone. The effectiveness of modern deep-cycle lead-acid batteries ranges between 70 and 75% [18]. Today, lead-acid batteries are one of the most important battery types used in the electric vehicle industry. They are a reliable power source because they can provide the high discharge currents required for an automobile's starter motor. Internal resistance determines the quantity of current that a battery can provide. Due to the exceedingly low internal resistance of lead acid batteries, even a relatively small battery can produce several hundred watts for a few seconds. Lithium batteries have ten times the internal resistance of lead acid batteries, so a lithium ion battery with the same voltage can only deliver one-tenth the peak current. Rapid discharge of a battery causes heat and other effects that can cause the battery's components to expand. Lead-acid batteries are basic and durable devices. In contrast, lithium-ion batteries are not safe in extreme temperatures and are prone to detonation. They are nearly entyrely recyclable, and the infrastructure for industrial production already exists. The cost is another important factor or advantage of lead-acid batteries. They are approximately 25% less expensive than an equivalent lithium-ion battery of the same capacity [18]. They tolerate float charging at a constant voltage, which makes battery management much simpler. Finally, lead-acid batteries function marginally better at low temperatures than all other types. During charge-discharge, lithium-ion batteries are more expensive and significantly more fragile.

5.1.4. Importance of lithium ion batteries in electric vehicles

The commonest type of battery currently in use in electric vehicles is the lithium-ion battery. This type has replaced lead acid battery technology in most models of electric vehicles on the road. Though there is constant comparison as to which technology is better between the two, each has its own merits and demerits. The use of lithium-ion batteries has experienced a substantial surge in recent years. This is attributed to the extended lifespan, high power density, and cost-effectiveness of Li-ion batteries [19]. Lithium-ion batteries provide several key characteristics that render them highly suitable for implementation in electric vehicle (EV) applications, including enhanced energy density, extended cycle life, and expedited recharge capabilities. Lithium-ion batteries provide a notable power-to-weight ratio, hence enabling electric vehicles to store a greater amount of energy relative to their weight [13]. A Li-ion battery weighs around five times less than a lead acid battery. A compact battery is much needed in EVs. A lighter battery will contribute to lesser energy consumption, and the EV can travel more on a single charge. This type also has higher energy efficiency than other technologies. Most lithium-ion battery parts are recyclable, making them a contributor to sustainability. This type has various safety features. Different safeguards have been implemented to protect batteries during repeated rapid charging sessions and ensure the safety of users. Li-ion batteries also have a feature of automatic disconnection**,** which disconnects the battery when the vehicle is idle, thereby protecting it from improper use by drivers [20].

The Li-ion battery technology seems quite promising but has its own share of demerits, like every other technology. These batteries are costly as compared to their counterparts. They are very sensitive to extreme temperatures, making EVs vulnerable for use in very hot or very cold regions [21]. Although these batteries can be recycled, the process is expensive and time-consuming. Low energy density is one of the major setbacks of this type. These disadvantages make electric vehicles an expensive choice as compared to their gasoline counterparts.

5.1.5. Coulombic Efficiency

Coulombic efficiency (CE) is a measure of the efficiency with which electrons travel within a battery during charge or discharge. It is also referred to as current efficiency and occasionally as faradaic efficiency [22]. In other words, it defines the movement of charges within a system, which in turn produces an electrochemical reaction. The determination of efficacy is commonly achieved by the application of the coulomb counting method. This approach plays an important role in ascertaining the SoC of a battery, hence facilitating the determination of the range and energy consumption of an electric vehicle [23]. The CE can be defined mathematically as the ratio of the total charge extracted from the battery during the discharge process to the total charge supplied to the battery during a complete cycle [22]. Lithium-ion batteries exhibit exceptional coulombic efficiency, often surpassing 99 percent, when charged at a modest rate. According to a study, the efficiency of lead acid batteries is comparatively lower, approximately 90 percent, when compared to lithium-ion batteries [3]. A battery with a high CE has an extended cycle life. Despite the fact that the CE of lead-acid batteries is nearly 10% less than that of lithium-ion batteries, there are similarities. As batteries start completing their charging cycle, they become warmer, which has a negative effect on CE performance. Low efficiency may be caused by lower charge acceptance rates or an increase in self-discharge as the battery warms up during its charging period. The performance of a battery is significantly influenced by factors such as temperature and battery age. The best efficacy of all batteries is found when the SOC is in the range between 30 and 70 percent [3]. The determination of CE and SoC assumes significant importance in the context of EVs, given that the range of EVs is dependent upon battery performance. A higher CE value signifies an extended and resilient battery lifespan.

5.2. Battery modelling

Electric vehicles are an important component of the collaborative effort that is being made worldwide to lower the carbon footprint and produce a cleaner energy cycle. The energy from batteries has several advantages over fossil fuels, because of which different types of batteries are now widely used in electric vehicle applications. High energy as well as power density, a low self-discharge rate, and a very low or no memory effect are a few merits of batteries that make them suitable for EV use. The modelling of batteries serves as the basis for the design and management of batteries. It is an excellent way to predict and estimate battery parameters required for a variety of applications. Battery ageing is dynamic in nature and depends on its physical properties. Battery life can be enhanced by optimising the power that is being consumed and extracted from the battery. Studies show that continuous draws of high current inhibit its residual capacity [24]. The efficiency of a battery is also largely determined by its nominal voltage, capacity, temperature, age, and number of cycles. Predicting battery behaviour ensures safe and efficient operation, thereby avoiding battery malfunctions caused by overcharging, overdischarging, or extreme temperatures. Battery models can also be used to effectively estimate key operating parameters such as coulombic efficiency, state of charge, and state of health, which are non-linear and otherwise quite difficult to measure physically. The two primary domains of battery modelling are the estimation of battery performance and battery design. The field of battery parameter characterization and performance evaluation has garnered far more attention than its design portion [23], due to the fact that battery behaviour or its performance has been more researched than its design aspect. Batteries are modelled for a variety of purposes, including the prediction of vehicle performance. These models differ in complexity, input parameters, available outputs, and overall accuracy [25]. Models emphasising the performance of vehicles rely on the prudent evaluation of performance data from a battery rather than its internal chemistry. The modelling of a battery holds significant importance in the examination, anticipation, and analysis of the real-time functioning of batteries. The goal and significance of battery modelling can be succinctly explained for the following reasons [26].

a) They can be used in the development of accurate and efficient battery management systems.
b) They can be made to enhance battery capacity and improve the charge-discharge methods of batteries.
c) They can be used to examine how power usage affects the battery.
d) They can be used to ensure safety while using batteries by preventing overcharging or overdischarging.
e) These models are the best to study battery behaviour under different operating conditions.
f) They can be used to extract battery parameters required for specific applications, especially those involved in vehicle performance.

5.2.1. Categorisation of battery modelling

Battery modelling has progressed and evolved variedly over the years on the basis of accuracy and complexity. The battery modelling (BM) problem is a constrained, multi-dimensional, mixed variable, non-convex, non-linear optimisation problem [26]. These models are generally sectioned into three groups according to the levels of physical interpretation of battery electrochemical processes presented in the models [6]. They are:

1. white-box models: electrochemical model
2. grey-box models: reduced-order model and equivalent electric circuit models
3. black-box models : neural network models, fuzzy control models

Different modelling strategies used for extracting the battery parameters are electrochemical, mathematical, electrical circuit-oriented, and data-driven [26]. Electrochemical models are primarily used for battery design [23]. Due to the nonlinearity of battery discharge, its modelling is quite complex. Theoretically, during a discharge cycle, the voltage is constant but drops to zero once the battery is depleted. The capacity would therefore be constant as well, and the entyre stored energy would be utilised. When a real battery is contemplated, this scenario is seen to be altered. The discharge process causes a gradual decrease in voltage and capacity, particularly for large discharge currents. Battery parameters in EECMs are usually identified by the collection of experimental data, which is then used for fitting the model. Battery models have been proposed using mathematical models to predict battery behaviour. These models are usually referred to as empirical models. Battery modelling can also be performed without considering any physical parameters of the battery. Prediction of battery behaviour can be best done using these models. They are grouped into black box models, of which the neural-network model is an apt example. The classification of various battery models has been illustrated in Fig. 5.5. The following section discusses a few battery modelling types.

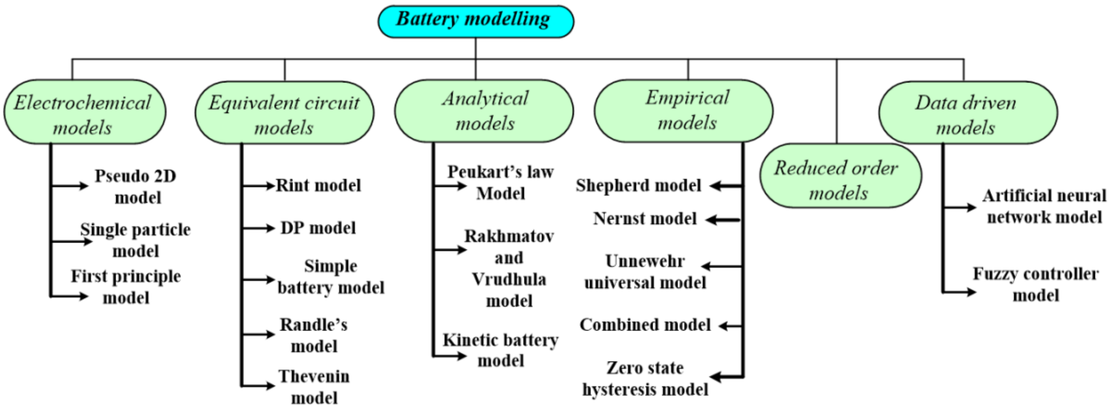

Fig.5.5 Types of battery modelling approaches

5.2.1.1. Electrochemical models

The chemical processes that take place inside a battery serve as the basis for electrochemical models. They fall under the category of physical models or white box and are employed to simulate the transient behaviour of battery cells [27]. The battery mechanism and processes can be expressed elaborately using this type of model, which makes it one of the most accurate battery modelling approach. This approach is best suited for battery designers but is difficult when practical application is required. These models, however, have their own share of demerits. Extensive detailing makes these models complex and challenging to configure [5]. Electrochemical models require an in-depth understanding of many battery attributes like the material used in the battery, chemical composition, conductivity, etc. This makes the acquisition of battery parameters difficult for many system designers and engineers. Using these models for on board systems increases computational expenses due to the complex numerical techniques needed during modelling. All electrochemical models are based on a few laws and equations of physics. They include Ohm’s Law,Fick’s Law, Faraday’s Law, and the Butler-Volmer equation. These laws demonstrate the chemical processes taking place within the battery. The processes include potential distribution in the electrodes, the pore-wall flux, and its deviation from the current flow in the electrolyte [27]. The main electrochemical models are the Single Particle Model (SPM), Pseudo-2D model and the First principle model.

a. Pseudo 2 dimensional model (P2D model)

This model was proposed by Doyle et al. and is based on porous electrode theory [28]. It is a model that examines the functioning of batteries, particularly those involving lithium and lithium ion cells. In this model, the positive and negative electrodes are regarded as multiparticles. Solid phase diffusion, electrolyte kinetics, and Butler-Volmer kinetics are all included in the P2D model [29–30]. To acquire battery parameters like voltage and current as a function of time, the P2D model's initial set of six coupled, non-linear differential equations had to be solved [6]. This model has also been used to estimate the salt concentration, reaction rate, and current density in the electrolyte as functions of time and location. The Dualfoil programme has been used to simulate this model. For a load profile that the user has chosen, it has been investigated how battery characteristics vary over time. The output data that was obtained can also be used to calculate battery life. The programme has a very high level of accuracy. Due to the program's high accuracy and effectiveness, it is frequently used for comparison and evaluation of alternative methodologies.

b. Single particle model (SPM)

This model is a also a prevalent electrochemical battery design. In contrast to the P2D model, it treats the electrodes as a single particle and assumes that the electric potential of the solid phase is constant within the electrode [31]. With this model, calculations of the voltage reductions in the electrolyte for increases in and states of charge may be made with little error. Additionally, the SPM model is often applied to lithium ion battery technologies. It treats the various chemical particle reactions occurring on inside the positive and negative electrodes as if they were one spherical particle [32–33]. The SPM model is straightforward and free of significant complications, but one glaring flaw is that the analysis procedure takes a long time. This type has a focus on slowly charging and draining the battery. Additionally, simulation and estimation accuracy varies and is demonstrated to be subpar in some real-world situations. In addition, it uses curve fitting or an approximation to solve the partial differential equation as opposed to the P2D model, which has more equations and parameters [34].

c. First principle model

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The charge-discharge cycle of a battery causes changes in its chemistry as well as its parameters. The capacity of a battery diminishes with use. The first principle model is mainly used to simulate the capacity decline of the battery when it is put under constant current, constant voltage (CC-CV) charging [27]. The different chemical, physical, and electrochemical processes taking place inside the cell throughout the rest period and working circumstances are represented by the quasi-three-dimensional full-order physical models.

d. Other models

Apart from the aforementioned common electrochemical models, there are other models proposed by researchers. Song et al. [35] extended an isothermal model to include energy balance analysis in the prediction of the battery temperature. Wang et al. [36] and Gu et al. [37] proposed a micro-macroscopic coupled model for advanced batteries and fuel cells. The model takes into consideration a number of non-equilibrium effects encountered in applications involving high-power-density and high-energy-density power sources, e.g., in EV and HEV applications.

5.2.1.2. Reduced order models

Reduced-order models are, in general, simplified derivatives of electrochemical models [38]. In this type of model, some additional assumptions are made in addition to the traditional electrochemical models. Reduced order models are more preferred for control system based applications. Here, the electrolyte is considered a constant, thereby simplifying the model. Assumptions, though leading to simplification of the model, cause a loss of information in most cases as compared to a physical model. A simplified reduced-order battery model was reported by Domenico et al. [39], wherein the solid concentration distribution along the electrode was neglected and the diffusing material was considered a solid particle for each electrode. By integrating additional assumptions based on full-scale electrochemical models, Smith et al. [40] additionally suggested another reduced-order model suitable for control-oriented applications. Even with all their disadvantages, these models are accurate for specific applications, such as state-of-charge estimation and voltage prediction, and exhibit a low computational cost that is desirable for real-time implementations [6]. On board vehicles, these models can be used for the extraction of battery parameters using information about battery voltage and current.

5.2.1.3. Empirical models

Simple empirical equations are the building blocks of empirical models. These equations can be used to identify and determine various battery features, as well as describe non-linear battery behaviour. They are also called mathematical models or black box models. These models typically show a low accuracy rate and are used for specific current- and temperature-based applications only. Although the models are not very accurate, they are simple and hence are used for achieving real-time parameter identification and implementation. The approach involves determining output through the implementation of transfer functions without involving the mechanisms occurring inside the battery. Empirical models are easy to configure and provide a quick response. The accuracy of this type of modelling approach can be improved when it is combined with low level methods [41]. The common empirical models are the Shepherd model, the Unnewehr universal model, the Nernst model, the combined model, and the zero-state hysteresis model. The first four models are together grouped as classical models.

a. Classical model

The classical model is a simplified electrochemical model. Using a simple set of mathematical and polynomial equations, the empirical model describes the non-linear response of the battery compared to other higher-order complex battery models. Here, the output voltage is expressed as a function of the battery current and the SoC. These models comprise voltage sources that are connected with resistance to model different types of electrochemical batteries. The SoC of the battery is considered a state variable to avoid loop issues [42]. Conventional empirical models do not consider the hysteresis effect of the battery, and hence the results are not accurate during the relaxation period [43]. This type of battery model can be easily implemented using dynamic simulation tools like MatLab/Simulink [44]. The general Shepherd equation is given by:

$$v_t = K_0 - R_0 I_L + \frac{K_1}{SOC} \tag{4}$$

where v_t is the terminal voltage, K_0,K_1 are constants used to fit the model well,R_0 is the cell internal resistance, I_L is the load current (positive for discharge and negative for charge), and SOC is the state of charge of the battery. This model describes the electrochemical behavior of the battery directly in terms of voltage and current. The Unnewehr Universal model is a simplified version of the shepherd model and attempts to model the variation in resistance with respect to SoC .The generalised equation for this model can be expressed as:

$$v_t = K_0 - R_0 I_L + K_2 SOC \tag{5}$$

where v_t is the terminal voltage, K_2 is a constant for proper curve fitting,R_0 is the internal resistance, I_L is the load current and SOC is the state of charge of the battery. The Nernst model is also a modification to the Shepherd model and uses exponential function with respect to SoC.The expression can be generalised as:

$$v_t = K_0 - R_0 I_L + K_3 lnSOC + K_4 ln(1 - SOC) \tag{6}$$

where v_t indicates the terminal voltage, K_3 and K_4 are constants for proper curve fitting, R_0 is the internal resistance, I_L is the load current and SOC represents the state of charge of the battery.The combination of the above three models have resulted in better and more precise performance and thus is known as a Combined model. Consideration of additional battery parameters and chemical reactions of the battery can improve the accuracy of this model. The expression is as below:

$$v_t = K_0 - R_0 I_L + \frac{K_1}{SOC} + K_2 SOC + K_3 lnSOC + K_4 ln(1 - SOC) \tag{7}$$

where v_t indicates the terminal voltage, K_1,K_2, K_3 and K_4 are constants for proper curve fitting, R_0 is the internal resistance, I_L is the load current and SOC represents the battery SoC. Comparitive analyses have shown that the Nernst and Unnewehr universal model provides more accurate prediction of battery behaviour than the Shepherd model. The prediction of dynamic terminal voltage obtained using Nernst model has proven to be most accurate because it has requires two extra constants than the other methods thereby providing better results when curve fitting techniques are used [45].

b. Zero state hysteresis model

The zero-state hysteresis model is another common empirical battery model.This model considers the dynamic hysteresis voltage variation in addition to the instantaneous change in voltage hysteresis [27]. The model equation can be expressed as

$$V_t = V_{oc}(S_c) - I_k R_o - Hh_k \tag{8}$$

$$V_t = V_{oc}(S_c) - I_k R_o - Hh_k - HS_k \tag{9}$$

where S_c describes state of charge of the battery, H is the hysteresis level coefficient which is a constant and h_k indicates the battery hysteresis effect based on whether the battery is charging or discharging at that specific instant of time. The combined dynamic and instantaneous hysteresis model equation to obtain the battery terminal is described in equation (9) where S_k refers to the charging or discharging current.

5.2.1.4. Analytical models

Analytical battery modelling involves a higher degree of abstraction as compared to electrochemical and electrical circuit models. Feature specific battery characteristics or internal chemistry are not required in this approach. Battery behaviour and performance can be modelled with the help of only a few equations, making it much low in complexity and user-friendly than its counterparts. The most common approaches for analytical models are Peukart’s Law model, the Rakhmatov and Vrudhula model and the Kinetic battery model.

a. Peukart’s Law model

Battery life and behaviour can be well predicted by using the simplest of analytical models which is Peukart’s Law model. [46]. The rate of discharge of the battery shares a non-linear dynamic relationship with the battery life. These features are considered in this model, where the battery lifetime can be approximated as:

$$L = \frac{a}{I^b} \tag{10}$$

where L is the battery life, I is the discharge current, and a and b are experimentally acquired constants. The variable refers to and is equivalent to the battery capacity for all practical cases, and b is ideally equal to 1. However, it has been observed that the value of b lies between 1.2 and 1.7 for most types of batteries [47]. The Peukart’s Law model works best for constant, continuous loads.

b. Rakhmatov and Vrudhula model

Rakhmatov and Vrudhula proposed and created this battery framework [46]. It is an extension of Peukert's law for variable or non-constant loads. This model is used to analyse the diffusion process that the active material in the battery goes through. In a region of length l, the diffusion is thought to be one-dimensional. The diffusion process based on Fick's law is described by

$$\begin{Bmatrix} -J(x,t) = D\frac{\partial C(x,t)}{\partial x} \\ \frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2} \end{Bmatrix} \tag{11}$$

Here, $C(x,t)$ is the concentration of the active material at a time *t* placed at a distance $x \in [0,l]$ from the electrode, J(x, t) is the flux of the active material at a time *t* and position x, and D is the diffusion constantCalculating the time at which the concentration at the electrode's surface falls below the cut-off level is necessary to determine the battery lifetime.

c. Kinetic Battery Model

Kinetic Battery Model (KiBaM) is another analytical model proposed and reported by Manwell and McGowan [48–50]. This battery model is quite practical and obtains the name kinetic because it is centred on a chemical kinetics process. The model distributes battery charge into two sections, namely, the available-charge section and the bound-charge section. The purpose of the bound charges is to provide electrons to the available charge section, which in turn provides them directly to the load. The KiBaM model can also be used to model the battery as a voltage source with an internal resistance. The change of charge in both sections can be expressed by the following set of differential equations:

$$\begin{aligned}\frac{dy_1}{dt} &= -I + k(h_2 - h_1)\\ \frac{dy_2}{dt} &= -k(h_2 - h_1)\end{aligned} \tag{12}$$

The difference in the height between the two sections and the parameter k determine the rate at which the charge flows. C refers to the charge present in the available charge section of the battery. The above set of equations is intialised at

$$y_1(0) = qC \; and \; y_2(0) = q(1 - C) \tag{13}$$

Where, q is the total battery capacity. h_1 and h_2 can be written as : $h_1 = y_1/c$ and $h_2 = y_2/(1-c)$. The voltage during discharge can also be modelled using the KiBaM model. It differs according to the discharge depth. The voltage is given by:

$$V = E - IR_o \tag{14}$$

where I is the discharge current and R_0 is the internal resistance. E is the internal voltage, which is given by:

$$E = E_0 + AX + \frac{CX}{D-X} \tag{15}$$

where E_0 is the internal battery voltage of a fully charged battery, A is a parameter reflecting the internal battery voltage's initial linear variation with state of charge, C and D are parameters reflecting the decrease in battery voltage during gradual discharge, and X is the normalised charge taken out of the battery. The battery's discharge data can be used to determine these parameters.

5.2.1.5. Data-driven models

This type of battery modelling approach solely bases its analysis on the data available from batteries without interfering with their chemistry or characteristics. Data-driven models are also known as black-box models. These models are mostly used in battery management systems of electric vehicles as they can be accurately used to predict battery SOC, which otherwise is quite difficult due to its non-linear nature. There are various factors that affect its state of charge and health, and a data driven model aids in preventing issues like overcharging or discharge that may harm the battery permanently. These models are generally used for Li-ion batteries because the performance of Li-ion varies with ageing, which makes SoC estimation complicated. These types of models are beneficial in scenarios where the mathematical model is unknown,or uncertainities are so high that empirical equations cannot be used to model them. Parameters like current, voltage, temperature, and SOC are considered to simulate this model for the estimation of the battery system behaviour. A few data driven models are the fuzzy controller [51–52], the support vector machine [53], and the neural network model [54–55]. Large amounts of data storage and analytic tools are needed for implementing these models. Machine learning techniques easily adapt to the system and need minimal resources. These models use neural logic to build the battery model estimator to calculate SoC, which considers temperature, current, and SoC as inputs and battery voltage as output, and also predict the charging-discharging pattern of a battery.

5.2.1.6. Electrical-circuit models (EECM)

One of the most popular battery modelling approaches is the electrical circuit model. It is also known as a grey-box model. These models were first proposed by Hageman [56], wherein simple Pspice circuits were modelled to simulate the behaviour of nickel-cadmium, lead-acid, and alkaline batteries. The ECMs replicate the electrochemical processes of a battery using simple equivalent electrical circuits. They are widely used for battery management systems in vehicles and other electric vehicle based applications. The modelling criteria for most of the batteries developed using these models are usually the same. Battery impedance is affected by SOC and temperature. These features are considered to establish the battery behaviour in these models. The model mostly consists of a capacitor representing the battery capacitance, a resistor representing the internal resistance, a circuit for discharging the battery, and a voltage versus state-of-charge (SoC) lookup table. These types of models require some effort during their configuration but are simpler than electrochemical models, and hence their computational cost is low. Experimental data of battery behaviour is used in the simulation of these models, which are reported to have an error of around 10% [5]. To simulate the behaviour of the battery, EECMs include a variety of electrical components, including a voltage source, resistors, capacitors, and occasionally a non-linear component like Warburg impedance. These models are mainly divided into impedance based EECMs and voltage-current (VI)-based EECMs [6].

a. ***Randle's equivalent model***

This model is an EECM based on impedance. Also known as Electrochemical impedance spectroscopy (EIS), this model examines impedance over a wide frequency range [6]. The behaviour of the battery in this model is investigated using the battery's impedance. Because estimating the impedance is difficult when dealing with batteries, this model's complexity is relatively high. Figure 5.6 shows the randle model's equivalent circuit model, where R_i stands for internal resistance, L for inductance, C for capacitance, R for nonlinear resistance, and ZW for nonlinear Warburg impedance.

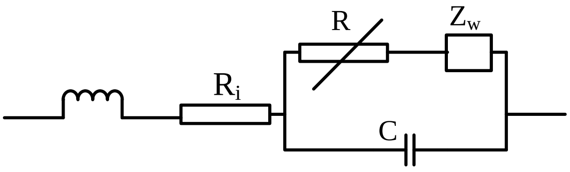

Fig.5.6 Randle's EECM to model battery impedance response

The Warburg impedance has a constant phase of 45° and a magnitude inversely proportional to the square root of the frequency as

$$Z_w = \frac{A_w}{\sqrt{\omega}} + \frac{A_w}{j\sqrt{\omega}} \tag{16}$$

where A_ω is the Warburg coefficient, ω represents the angular frequency, and j is the imaginary number. For investigations at low frequencies, the inductance can be disregarded. By adjusting the model to the battery's measured EIS, the model's parameters can be found. Since the model is nonlinear and complex and the parameters depend on the operating conditions, nonlinear parameter identification methods are typically needed, and they take a lot of time [6]. This approach studies and models the open circuit voltage, internal resistance, capacitance, and Warburg impedance using Matlab/Simulink blocks, based on the physical principles governing battery electrochemical processes. Analyses are also performed on the impact of ffrequency and current on battery parameters. Model parameters are determined by fitting the model using non-linear identification techniques to derived impedance data.

b. ***V-I based EECM model***

The assessment of impedance on vehicles presents a range of limitations, prompting researchers to employ existing onboard estimations such as terminal voltage, load current, and temperature to simulate battery activity. In this model type, the Warburg impedance is commonly disregarded due to its non-linear characteristics, which would provide further complexity to the problem. It utilises a linear Equivalent Electrical Circuit Model (EECM) structure, which comprises an ideal voltage source, a resistor, and a series of RC networks. This configuration is employed to accurately represent the battery's dynamic characteristics. The battery's performance cannot be accurately characterised over a large range of state of charge (SOC), temperature, and current rate using a single constant equivalent electric circuit model (EECM) due to the battery's highly non-linear and non-stationary behaviour. The problem is resolved by the utilisation of a consistent EECM across a range of operational scenarios that together encompass the entyrety of the subject matter. Subsequently, it becomes feasible to ascertain the relationship between the model parameters and the prevailing operational conditions. One instance of such a model can be observed in the linear parameter variable (LPV) EECM [6]. Engineers are particularly drawn to the linear structure, configurability, and parameter identification capabilities of an LPV EECM. In the context of most system design applications, it may be argued that the model is adequately exact. Moreover, it is possible to replicate this phenomenon in several circuit simulation tools, incorporating pertinent electric circuits and onboard control systems. Given that the specific battery chemistry is not a prerequisite, an EECM can be employed with a wide range of battery varieties.

c. *Simple Battery Model*

One of the most frequently used model is the simple battery model. It is also commonly known as the Rint model [27]. The battery model consists of a constant equivalent internal series resistance R_o , battery terminal voltage V_t and an open-circuit voltage E_{oc}. A fully charged battery helps determination of E_{oc} with the help of open circuit measurement. Application of a load at the terminal aids the estimation of R_o . Although this model is often utilised, it fails to account for variations in internal impedance characteristics resulting from fluctuations in charge, electrolyte concentration, and sulphate generation. This model is primarily relevant in circuit evaluations wherein it is considered that the energy received from the battery is inexhaustible and the SoC is not a critical factor.

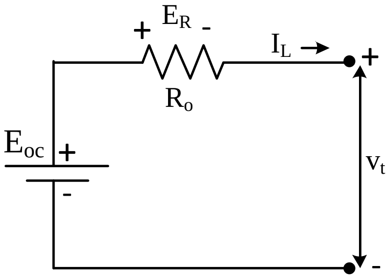

Fig.5. 7 Simple Battery Model

The expression for the simple Rint Battery model as shown in Fig.5.7 can be written as

$$V_t = E_{oc} - I_L R_o \qquad (17)$$

where V_t indicates the terminal voltage, E_{oc} is the open circuit voltage, R_0 is the internal resistance and I_L indicates the load current .

d. *Thevenin Battery Model*

The other often employed variant is the Thevenin battery model. The model establishes a connection between a parallel RC network and a series configuration, utilising the Rint model to describe the battery's dynamic characteristics [27]. The Thevenin model's analogous circuit is depicted in Figure 5.8. The symbol C_p is used to denote the capacitance of the parallel plates, whereas R_p denotes the non-linear resistance resulting from the contact resistance between the plate and the electrolyte. One notable drawback of the Thevenin battery model is in its assumption of constant elements, but in reality, the values of these elements are contingent upon battery circumstances. The mathematical representation of this paradigm is denoted by the following equation:

$$\dot{E_p} = \frac{I_L}{C_P} - \frac{E_P}{R_P C_P} \tag{18}$$

$$\text{and,}\quad V_t = E_\propto - E_P - I_L R_0 \tag{19}$$

where V_t indicates the terminal voltage, E_p is the voltage across the capacitor C_P, C_P is the equivalent polarisation capacitance to model the battery relaxation effect during charge and discharge,R_P is the equivalent polarisation resistance, R_0 is the internal resistance and I_L indicates the load current .

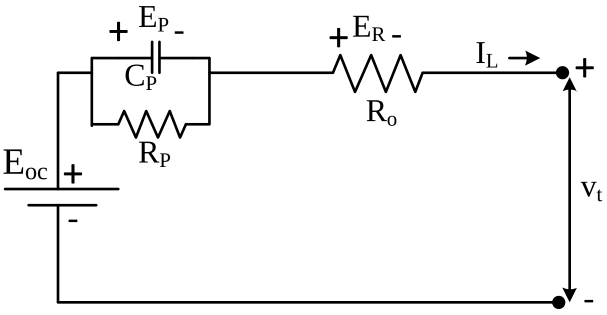

Fig.5.8 Thevenin Battery Model

*e. **Double Polarization (DP) Model***

The proposed model is founded upon the principles of the Thevenin battery model. A parallel RC network is incorporated in series with the Thevenin model to enhance the accuracy of the polarisation characteristics description [27]. The independent modelling of concentration polarisation and electrochemical polarisation is conducted, potentially resulting in enhanced accuracy of performance. The schematic representation of the model's corresponding circuit is depicted in Figure 5.9.

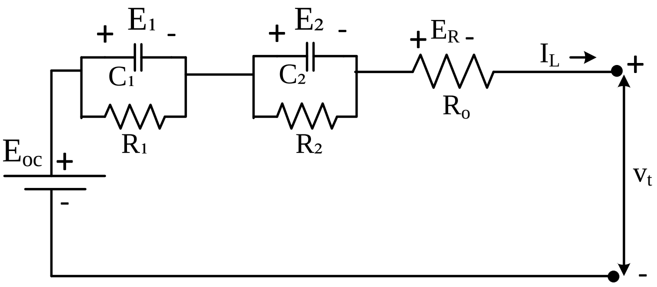

Fig.5.9 A DP Battery Model

The expressions of this model are as given by the following equations:

$$\dot{E}_1 = -\frac{E_1}{R_1 C_1} + \frac{I_L}{C_1} \tag{20}$$

$$\dot{E}_2 = -\frac{E_2}{R_2 C_2} + \frac{I_L}{C_2} \tag{21}$$

$$V_t = E_{\propto} - E_1 - E_2 - I_L R_0 \tag{22}$$

where E_1,E_2 are voltages across C_1 and C_2 respectively, V_t indicates the terminal voltage,R_0 is the internal resistance and I_L indicates the load current . A comparison of all the types of battery modelling approaches has been listed in Table 5.5.

Table 5. 5 Comparison of features of the different battery models

Model	**Merits**	**Applications**	**Time**
Electrochemical model	Highly accurate	Battery system design and diagnosis	Precise voltage calculation consumes much time
Reduced order model	Computational cost is low	SoC estimation,Control system application	Average time consumption
Empirical model	Low complexity	All kinds of energy storage sources	Simple and low time consuming
Analytical model	User friendly and less complex	Study performance and behaviour of all types of battery	Time consumption is low
Data driven model	Computational cost is low	Prediction of battery behaviour in EV/HEV	Battery chemistry and basics not involved so less time consuming
Electrical circuit model	Accuracy is high and time complexity is less	EV/HEV and battery management systems	Simple and so average time consuming

5.2.2. Simulation of equivalent electrical circuit battery model

Electrical circuit models are used to obtain a behavioural approximation of the response of a battery cell to different input currents or load conditions. Battery behaviour can be simulated by this model with the help of common electrical circuit elements like resistors, voltage sources, and capacitors[57]. Though these models are not as functional as physics-based models, they are used in most battery management systems because they exhibit a high degree of accuracy when predicting battery parameters in a dynamic manner. They are preferred for their simplicity and robustness. The fundamental behaviour observed in a cell is that it delivers a voltage at the terminals. The voltage source is thereby an important factor in equivalent circuit models (ECMs). The use of only a voltage source will make it a constant, which is rather impractical. ECMs include an equivalent series resistance (ESR) to describe the effect of load on the battery terminal voltage. This is called the simple Rint model. The model is used for simple electronic circuits. More complex applications require the inclusion of polarization which is done through the modelling of diffusion voltages. It is the departure of the terminal voltage when a certain amount of current is passed through the cell. The diffusion voltage can be closely approximated in a circuit using one or more parallel resistor capacitor (RC) sub-circuits. The model with one such branch of an RC circuit is known as the Thevenin model [57].

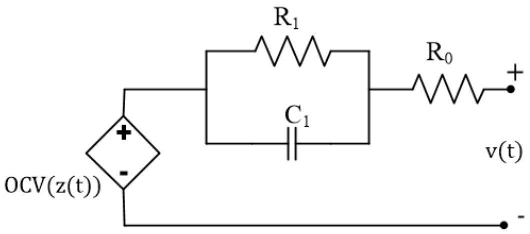

Fig.5. 10 Equivalent circuit model to model diffusion voltage

In the above figure,Fig.5.10 , v(t) is the terminal voltage of the battery, OCV is the open circuit voltage which is a function of SOC ,z(t), R_o is the ESR, R_1 and C_1 is the RC network which determines diffusion volatge of the battrey.The cell voltage can be defined as

$$v(t) = OCV\big(z(t)\big) - VC_1(t) - i(t)R_o$$

and the State of Charge of the battery can be modelled as

$$\frac{dz}{dt} = {}^{\eta(t)i(t)}\!/_{Q}$$

Where η(t) is the coulombic efficiency of the cell. It is assumed to be 1 when the current is positive (discharge) and less than 1 when the cell is charging. The magnitude of the current,i(t) is negative when it is on a charging cycle. Q is the total capacity of the cell measured in Ah. It is quite challenging to model CE accurately, but it is seen that consideration of the above results leads to precise results. The continuous-time model has two state equations and one output equation, which can be summarised as [57]

$$\frac{dz}{dt} = {}^{-\eta(t)i(t)}\!/_{Q} \tag{23}$$

$$\frac{di_{R1}(t)}{dt} = -\frac{1}{R_1C_1}i_{R1}(t) + \frac{1}{R_1C_1}i_R(t) \tag{24}$$

$$v(t) = OCV\big(z(t)\big) - R_1 i_{R1}(t) - i(t)R_o \tag{25}$$

However, while modelling batteries it is observed that calculations are mostly performed in discrete time domain. The above first order ordinary different equations (ODE) are therefore converted to discrete-time domain for the purpose of modelling. The coupled equations can be summed up as follows:

$$z[k+1] = z[k] - \frac{\Delta t}{Q}\eta[k]i[k] \tag{26}$$

$$i_{R1}[k+1] = \exp\left(-\frac{\Delta t}{R_1C_1}\right)i_{R1}[k] + \left(1 - \exp\left(-\frac{\Delta t}{R_1C_1}\right)\right)i[k] \tag{27}$$

$$v[k] = OCV(z[k]) - R_1 i_{R1}[k] - i[k]R_o \tag{28}$$

Equivalent circuit models are sometimes seen to include an impedance known as the Warburg impedance. The Randles circuit is the most frequently used when this impedance is considered [57]. It facilitates the inclusion of electrolyte resistance, charge-transfer resistance, and a double layer capacitance. These effects are prominent in lithium ion cells, and since our main focus area is lead acid batteries, they have been neglected in our analysis. Moreover, no simple differential equation can represent this impedance precisely, which makes circuit simulation impractical. But studies suggest that multiple parallel RC networks can be used in series to model a Randles circuit.

The existing models of lead-acid batteries are characterised by high costs, challenges in parameterization, and a time-consuming setup process. The development of lead-acid battery models can present challenges in terms of cost, time, and modelling complexity. The mathematical simulation of a basic electrical circuit model has been conducted to assess the performance of electric vehicles.

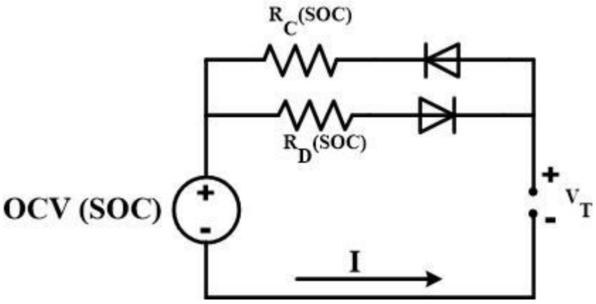

Fig.5.11 A simple electrical circuit battery model

Figure 5.11 depicts a simple equivalent electrical circuit model of a battery. R_0 is presumed to be the internal resistance of the battery in this figure. The open circuit voltage is one of the most important parameters that must be determined while simulating a model. Open Circuit Voltage (OCV) is found to be directly proportional to State of Charge (SoC) in lead acid batteries [18]. It has been discovered that the rate at which the battery is charged or discharged influences the internal resistance of these batteries. R_D(SOC) and R_C(SOC) represent the battery's internal resistances during discharging and charging, respectively. V_T is the terminal voltage of the battery. It is the voltage obtained when a battery is subjected to a load. Batteries are comprised of small cells that constitute a unit. The nominal voltage of an individual cell in a lead acid battery is 2.1 volts. Therefore, the variation in open circuit voltage with respect to the SOC is illustrated in Figure 5.12. It is evident from the graph that the OCV is approximately proportional to their SoC. The continuous line in the diagram represents the actual decline in OCV, while the dotted line is for reference only. It demonstrates that the OCV of one cell of an entyrely discharged battery is equivalent to around 2.0 Volts. Given that the SoC ranges between 0 when empty and 1 when full, the equation (23) for the OCV of a lead acid battery can be written as [18].

$$E = n * \left(2.15 - SoC * (2.15 - 2.00)\right) \quad (29)$$

where n denotes the amount of cells present inside the battery. The internal resistance in most cases is constant for a specific battery but is observed to get affected by working temperatures and SoC at times.

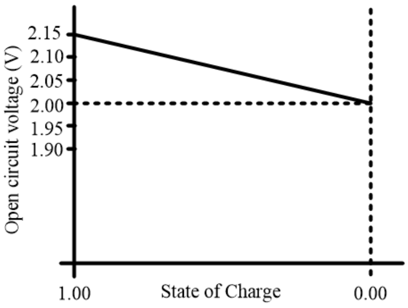

Fig.5. 12 Change in OCV with respect to SoC in one cell of a lead acid battery.

Battery modelling helps to study the charging and discharging pattern of a battery.The model that has been simulated consists of mathematical equations that can describe what is happening inside the battery.This model is based on a SOC-OCV relationship. Although there are several methods to calculate SOC, the most common method known as the Coulomb Counting method has been used here. The continuous time model equations are as below:

$$V_T = OCV(SOC) - I * R(T, SOC) \quad (30)$$

$$SOC = SOC_0 - \frac{1}{C_n} \int_o^t I(t)dt \quad (31)$$

This work also includes the analysis of a lead-acid battery model included in MATLAB. The model has been simulated in Simulink on the basis of model equations reported by Jackey in 2007 [58]. The battery model accepts a current input and produces outputs for the voltage and SOC of the battery [59]. The equivalent circuit model diagram of one cell of a lead acid battery has been illustrated in Fig. 5.13. It consists of one parallel RC pair and is a type of Thevenin battery model [60].

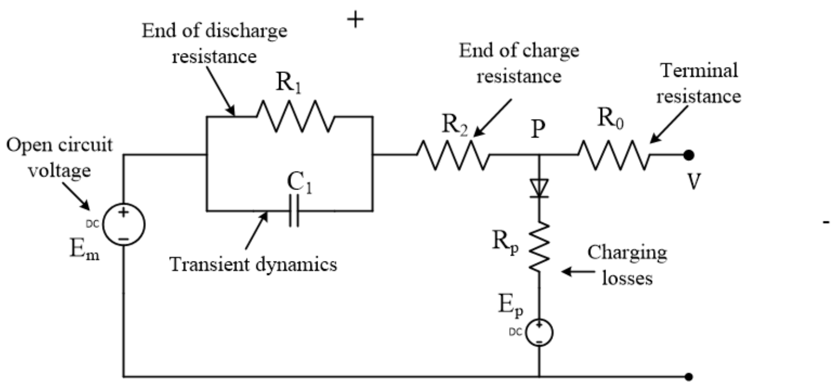

Fig.5. 13 Equivalent circuit model of one cell of a lead acid battery[59]

Every equivalent circuit element is derived from nonlinear equations. The equations encompass both battery states and parameters. The parameters of the equations are contingent upon constants that have been determined by empirical means. The variables considered in the study encompassed the temperature of the electrolyte, the amount of stored charge, and the voltages and currents at various circuit nodes [58]. For the purpose of simulation, some constants have been assumed.The equations that are presumed to be true have been discussed in the following section. The open circuit voltage (E_m) can be formally defined as the potential difference measured in Volts across the terminals of a circuit while no current is flowing through it and has been expressed as:

$$E_m = E_{m0} - K_E(273.15 + T_E)(1 - SOC) \tag{32}$$

where E_{m0} indicates the OCV at full charge, K_E is a constant used in simulation which is equivalent to $0.58e^{-3}$V/ ℃ and T_E is the electrolyte temperature in ℃. The terminal resistance , R_0 has been mathematically modelled as

$$R_0 = R_{00}(1 - A_0(1 - SOC)) \tag{33}$$

where R_{00} is the value of R_0 when battery is fully charged and A_0 is a constant value of -0.30. The resistance in the main branch varies with depth of charge which increases exponentially as the battery undergoes a discharge and can be calculated as [61]

$$R_1 = -R_{10}\ln(DOC) \tag{34}$$

And the capacitance C_1 can be expressed as

$$C_1 = \frac{\tau_1}{R_1} \tag{35}$$

Here, R_{10} is a constant factor of 0.7mΩ , DOC is the depth of discharge of the battery and τ_1 is a time-constant. The resistance R_2 is exponentially proportional to the battery SOC. It is mainly affected during the charging cycle.It can be denoted by the following equation[61]:

$$R_2 = R_{20} \frac{\exp[A_{21}(1-SOC)]}{1+\exp(\frac{A_{22}I_m}{I^*})} \tag{36}$$

where R_{20} is a constant value of 15 mΩ, A_{21} and A_{22} are constants of value -8 and -8.45 respectively,I_m is the main branch current and I^* is the nominal battery current in Amperes.The SOC in the model has been formulated using the equation below:

$$SOC = 1 - \frac{\int_0^t i_m(t)dt}{C(0,T)} \tag{37}$$

where the SOC is calculated by integrating the main branch current over a time interval of (0,t). C is the capacity of the battery[60].

5.2.3. *Simulation results*

The simulation-based battery model has been used to efficiently predict the battery behaviour of a lead acid battery. Information of charging and discharging cycles were used to obtain parameters like the terminal voltage, efficiency and State of Charge.These outcomes were observed to be consistent with experimental outcomes. A MATLAB simulink environment has been used to build the battery model which has been depicted in Fig.5.14.

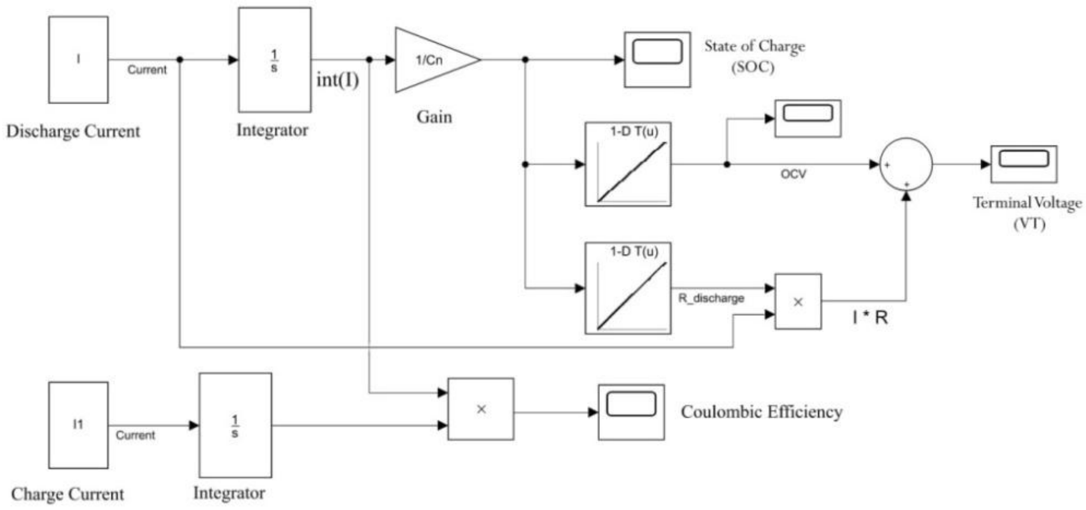

Fig.5. 14 Simulink model of the basic electrical circuit battery model

The open circuit voltage (OCV) and the State of Charge (SOC) of a lead acid battery have been depicted in Fig.5.15 and Fig.5.16, respectively. It can be seen that the model anticipates battery behaviour quite well. The current discharge rate was preset at 8A, thereby consuming approximately 3.25 hours to completely discharge the battery. This is evident in Fig.5.15, where the OCV is seen to be diminishing. The OCV is also observed to alter from approximately 26 Volts when fully charged to 23.8 Volts when completely discharged. Fig.5.16 shows the SoC versus OCV curve during a lead acid battery discharge cycle. When the OCV decreases during the cycle, the SoC of the battery decreases from 1 (100%) to 0(0%). Therefore, the higher the OCV, the greater is the State of Charge of the battery.

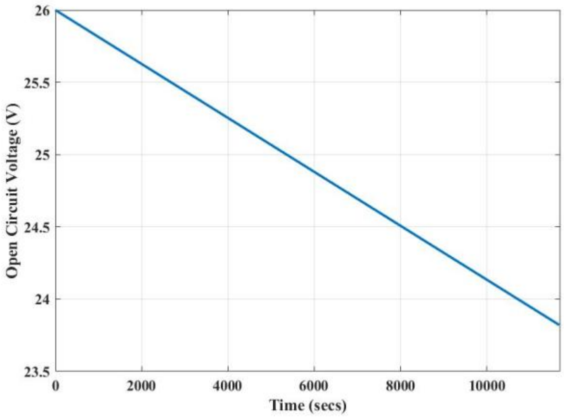

Fig.5. 15 The open circuit voltage change in a dicharge cycle of a lead acid battery

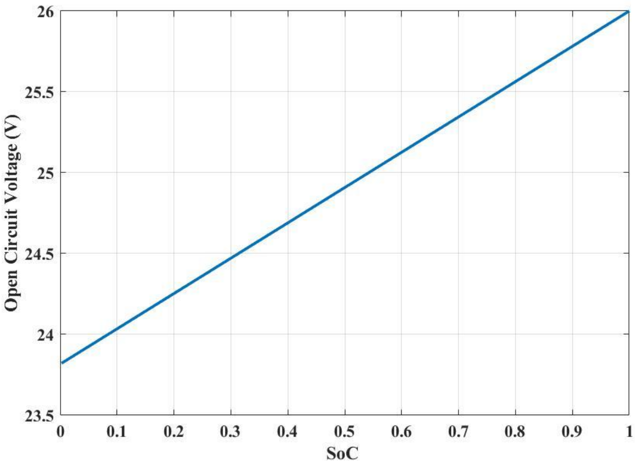

Fig.5.16 The open circuit voltage versus State of Charge in a lead acid battery

The lead acid battery model from MATLAB was analysed with satisfactory results for implementation. The battery model is depicted in Fig. 5.17. The battery was simulated to discharge at 5A and then be charged at 5A. The load current has been shown in Fig 5.18. The plot shows that the battery is discharged for around 5 hours and then charged for 2 hours before discharging it again. The terminal voltage trend has been depicted in Fig.5.19. It can be clearly observed how the charge decreases when the battery is being discharged and then again starts to increase when the battery starts charging. The SOC of the battery has been plotted in Fig.5.20. An SOC of 1 indicates that the battery is fully charged (100%) whereas 0 (zero) indicates that the battery is nearly depleted. The figure illustrates that the SOC slowly starts decreasing when the battery is put on discharge but starts to rise when the battery is in charging mode.

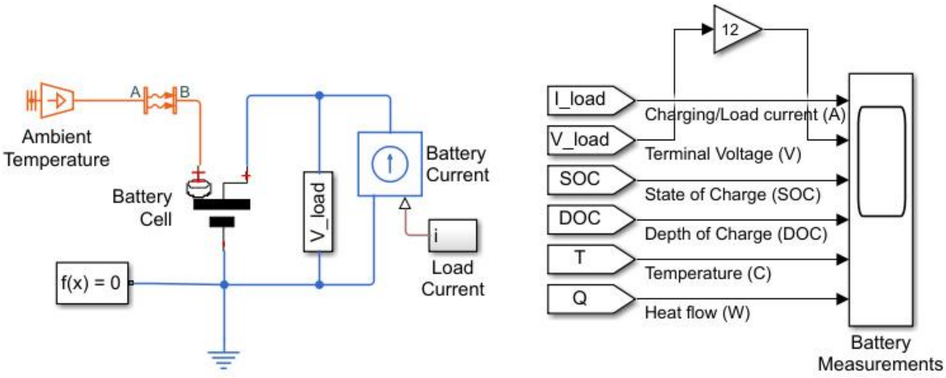

Fig.5.17 The lead acid battery model as implemented in MATLAB

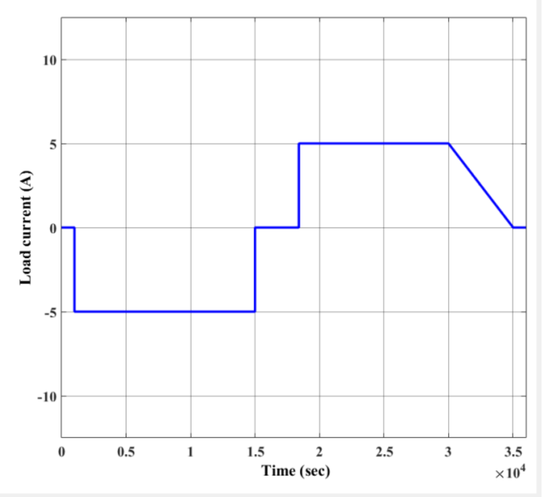

Fig.5.19 The battery undergoing 5A charge and discharge cycles

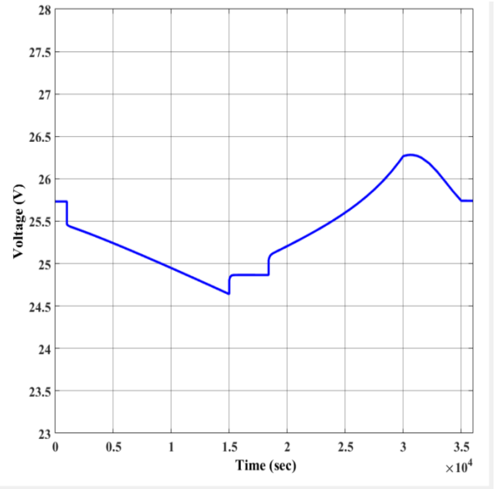

Fig.5.18 The terminal voltage of the battery

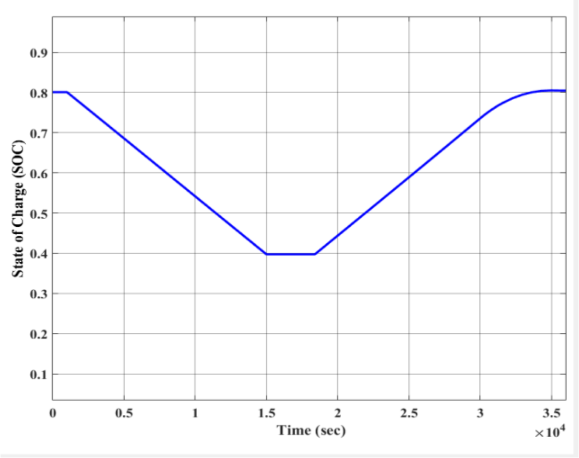

Fig.5. 20 The state of charge of the battery

Battery modelling therefore allows extraction and analysis of various parameters and their behaviour that can be used for complex electric vehicle based applications.

5.3. Coulombic efficiency estimation

The estimation of battery parameters, including coulombic efficiency, is an important analysis when battery performance is concerned. The battery source is a crucial constituent in an electric vehicle, and therefore, acquiring information about battery parameters greatly aids in the energy and range estimation of an EV. Numerous charge and discharge cycles are required when coulombic efficiency has to be measured. In this section, a Coulombic efficiency estimation technique has been presented. The system is simple, automated, user-friendly, and can be used for parameter extraction from batteries. It is a universal setup that allows testing of any kind or type of battery.

5.3.1. Proposed design

The Ampere-hour method is used extensively as the most common strategy for assessing the battery SoC in EVs [62]. The proposed method for extracting battery parameters as well as determining coulombic efficiency is based on a motor-generator coupling technique. This method enables the test battery to be discharged at constant current rates by the application of loads. This technique can extract and record both voltage and current data in real time. For the investigation, lead acid batteries have been used. A motor-generator set is comprised of a motor and a generator that are mechanically linked through a shared shaft. The equipment in question is utilised for the purpose of transforming electrical power from one form to another. This arrangement transforms electrical energy into mechanical form. For the coupling to function, the rated speeds of both the motor and the motor acting as the generator must be the same [63]. In this configuration, both input and output power is electrical, but mechanical torque is present in the power transfer between machines. This ensures the electrical separation of the two electrical systems [63]. The coupling configuration makes it easier to apply electronic loads to the system. Consequently, the test battery can be discharged at varied current rates. The load in the system is administered electronically, which aids in maintaining a constant current during a specific operation cycle. Discharge of the test battery is done at varying current rates by electronically applied constant resistive loads. However, the charging procedure utilises a charger equipped with sensors to estimate the current. Utilising the coulomb counting method, the state of charge and coulombic efficiency of the test battery can be determined. The charge-discharge cycle can be observed in real time, which facilitates the determination of key battery parameters such as Coulombic efficiency (CE) and state-of-charge (SoC). As a result of the inherent variability in battery performance, the energy storage system experienced multiple charge and discharge cycles, characterised by fluctuations in the applied current rates. The experimental configuration incorporates sensors to provide accurate data collection. The results of the charge-discharge have demonstrated efficiency and consistency. The obtained coulombic efficiency can then be used to calculate the EV's range. This work can be further developed to include the design and development of a system that provides sustainable renewable energy solutions. The estimation of energy consumption takes into consideration vehicle dynamics, aerodynamics, traffic flow, battery parameters, and weather in order to accurately determine the range of electric vehicles and thereby improve their energy efficiency. The primary advantage of this system is that it is portable, simple to operate, inexpensive, and capable of testing all varieties of batteries. The proposed system is straightforward and has produced positive results.The system that has been proposed is characterised by its simplicity and has yielded favourable outcomes. The battery parameters that have been acquired play a vital part in the calculation of the range during eco-routing navigation of electric vehicles, as well as in various other applications.

5.3.1.1. *Experimental set-up*

The experimental set-up for the proposed method consists of two main segments; the motor segment and the generator segment. Two motors are connected end-to-end through a common shaft, as depicted in Fig.5.21. The entyre set-up consists of the battery source to be tested, a resistive load (24V DC bulbs), and current sensors. The battery used for the experiments is a 24 V, 26 Ah lead acid battery. It also comprises a power unit, a controller unit, which consists of microcontrollers, an interfacing module, and a laptop for data acquisition and evaluation. The discharging and charging currents are sampled and measured at every instant of time by Hall-effect current sensors that are connected to the circuit. During a particular cycle, the sensors detect the change in output voltage and send it to the microcontroller. The current can then be determined accordingly. The load is fixed with the help of a power circuit connected to the generator.

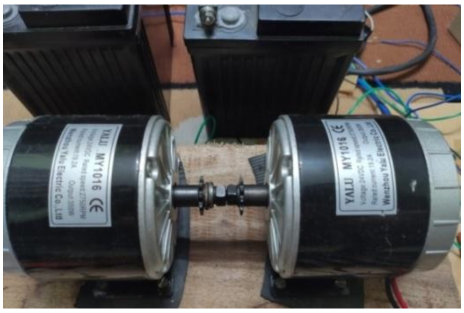

Fig.5. 21 Two motors connected along their shafts to form a motor-generator couple

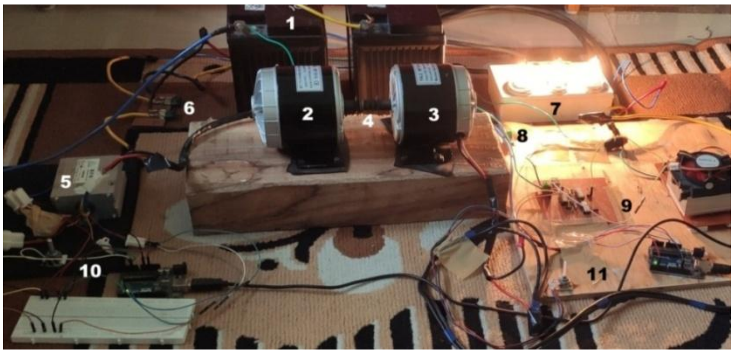

Fig.5. 22 The experimental set-up used to discharge the battery

Table 5.6 Circuit components used in the experimental set-up as in Fig.5.16

Number	Component
1	24V lead acid battery
2	PMDC Motor
3	Motor acting as generator
4	Common Shaft
5	Motor controller
6	Fuse
7	24V Resistive bulbs
8	Current Sensor
9	Power circuit for generator
10	Microcontroller for speed control of motor
11	Microcontroller for setting discharge rates

Fig. 5.22 shows the actual picture of the set-up used in this experimental method. The motor section and the generator section are electrically isolated. They have their separate power control units as well as microcontroller units. The components in Fig.5. 22 have been tabulated in Table 5.6 in serial order.

Fig.5. 23 The experimental set-up for charging

The experimental set-up used for charging has been shown in Fig. 5.23. The charger has been connected to a Hall-effect current sensor for the determination of an accurate current profile while charging the battery. The block diagram of the set-up depicts the entyre procedure taking place and is shown in Fig. 5.24. Two 350W PMDC motors are coupled to each other, thereby acting as a motor-generator pair. Each of the motors is controlled separately by power converters and a microcontroller attached to them. The current in the circuit is sensed using current sensors. The battery follows a charge-discharge cycle to complete a set. The test is then repeated at different current rates by adjusting the load on the generator side.

5.3.1.2. Circuitry and working principle

The proposed system consists of two sections comprising of a motor and a motor acting as a generator connected through a common shaft. The technical specifications of all the circuitry involved in the experiment have been listed in Table 5.7. A battery source is connected to the motor that is to be tested. The speed of the PMDC motor is steered by the pulse width modulation method (PWM). The motor controller comprises the power MOSFETs as well as the gate drive responsible for driving the motor. The application of voltage between the gate and source terminals of the MOSFET facilitates the production of current flow in the drain. The energy generated by the motor during operation is transmitted to the generator through the shaft. The generator is linked to a resistive load and possesses an independent power circuit that enables control over its operation. The application of an electrical load occurs on the generator section of the system. On increasing the load, the more current is drawn from the battery, and the DC bulbs acting as load get turned on, thereby reducing the speed of the motor. For our experimentation, the battery is discharged at a constant current every cycle. The amount of current drawn from the battery is continuously sensed through the hall current sensors connected in series with the battery and displayed in real-time through the microcontroller unit on a laptop.

Table 5.7 Technical specifications of circuitry used in experiment

Label No.	**Label Description**	**Specification**	**Application**
1	Lead Acid Battery	24V/26Ah	Test battery
2	Motor	24V/350W	For energy conversion
3	Generator	24V/350W	For application of load
4	Common Shaft	-	To connect the motor and generator

5	Power Circuit	H-bridge	To control the motor
6	DC Bulbs	24V/130ohm	Resistive loads to be applied for discharging
7	Current Sensor	30A Hall Sensor	Measuring charging and discharging currents
8	Potentiometer	10Kohms	Control speed of motor and for applying load

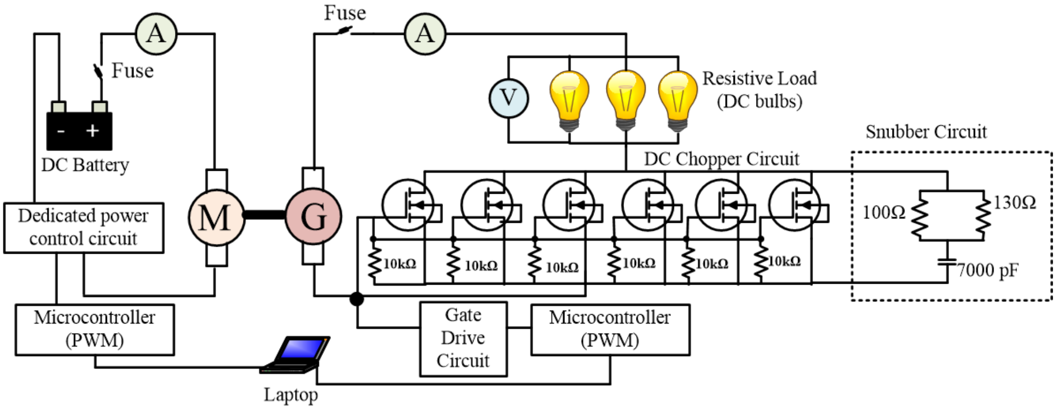

Fig.5.24 Circuitry and hardware of the proposed system

5.3.2. Calculations involved

The information of provided charge and consumed charge during a certain cycle of operation can aid in determining efficiency during that cycle. The Ah counting approach necessitates complete charge-discharge curve integration.It can be calculated by applying equation (38) given below [10].

$$Ah = \int_0^{Tt} I(t)dt \tag{38}$$

I(t) is the current during charge or discharge at time 't'. Ah counting method is achieved by piecewise approximation of the curve obtained through the above equation, and hence, the ampere hour can be simplified into the following summation as expressed in equation (39)

$$Ah = T.\sum_n I(n) \tag{39}$$

The expression for Coulombic efficiency is as follows [10],

$$Coulombic\ efficiency = \frac{Ah_c}{Ah_s} \times 100\ \% \tag{40}$$

Where Ah_c is the rate of discharge and Ah_s is the charge supplied to the load. The battery SoC is also a function of the current drawn or supplied to the battery and the time taken in doing so. The SoC is usually assumed to be one when the battery is fully charged and 0 when fully depleted. The SoC in discrete time can be mathematically derived by the given equation(41):

$$E[k+1] = E[k]\frac{\Delta t}{Q} i[k] \tag{41}$$

Where E[k+1] is the additional SoC which is dependent on the previous state E[k] SoC of the battery.Δt is the time interval between consecutive samples,i[k] is the current measured at that instant and Q is the total battery capacity.In this experiment ,the current drawn from the battery has been measured continuously by using a hall sensor.

5.3.3. Results and discussion

Using the proposed experimental set-up, several tests have been performed for the determination of the Coulombic efficiency and State-of-Charge of the test battery. One full charge and discharge completes one complete cycle. The battery is discharged with the help of a constant resistive electronic load, thereby drawing current from the battery at a constant rate. Therefore, by changing the loads, the battery can be discharged at various current rates. Obtained results help in estimating the coulombic efficiency of the power source.

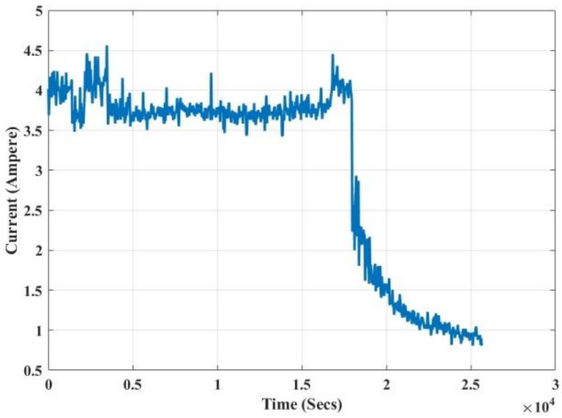

Fig.5. 25 Curve showing a discharge cycle at 4A

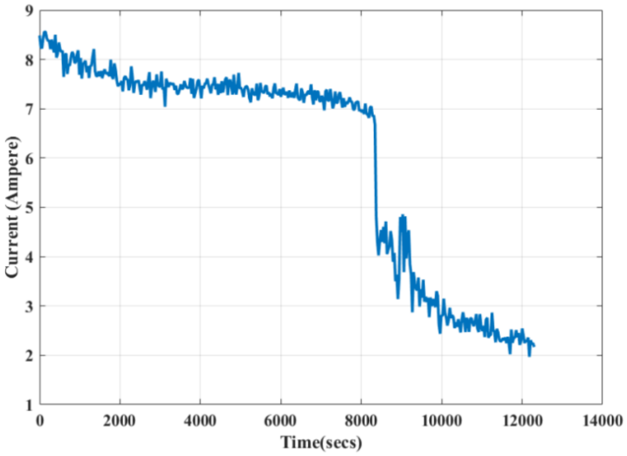

Fig.5. 26 Curve showing a discharge cycle at 8A

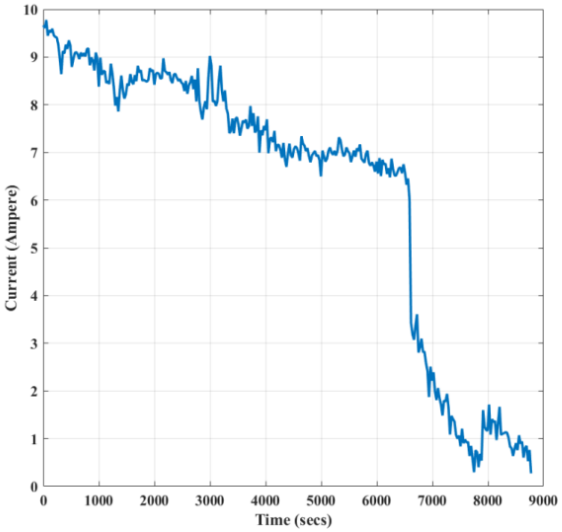

Fig.5. 27 Curve showing a discharge cycle at 10A

For accurate estimation of battery parameters, various rates of discharge were selected.The rate of discharge was 2A, 4A, 6A, 8A, 10A, and 11A. The aforementioned A here represents the unit of current, Ampere. Few of the discharge cycles of the current rates have been depicted in the figures. The discharge curve when the battery is discharged at a constant current rate of 4A is depicted in Fig. 5.25. Despite the fact that a constant current method has been utilised in practical systems, it can be observed that the current almost reaches zero when the battery is completely discharged. Figures 5.26 and 5.27 illustrate the discharge trajectory when the battery is discharged at a constant current rate of 8A and 10A, respectively. It is evident that this curve also exhibits a comparable trend. The test battery is a 24V/26Ah lead acid battery; therefore, a current of 8A should discharge the battery in approximately 3.25 hours, as shown by the curve. Also, when the current is discharged at a rate of 10 A, the time should be approximately 2.6 hours, which is roughly in line with the trajectory depicted in Fig. 5.27. In the graph, the total time required for a complete discharge cycle is approximately 2.5 hours, or 9000 seconds. To obtain the results, the battery was continuously charged and discharged at varying current rates. The discharge cycles at the various discharge rates have been compared. When the battery is discharged at the lowest rate of current, it takes the longest time to reach zero SOC .It can be seen that the curve conforms to the theoretical calculations for the rated time of discharge for a particular cycle.In Fig.5.28, for instance, a 6A discharge lasts approximately 15000 seconds, which equates to 4.16 hours.Similarly, the theoretical calculation predicts that a 26Ah battery discharging at a rate of 6A will require 4.3 hours to completely discharge. Figure 5.28 depicts a comparative analysis of discharging the battery at various current rates. Batteries are energy storage devices whose capacity is measured in Ampere-hours (Ah). When the battery is discharged, which occurs when a load is connected, it begins to extract energy from the battery. Discharge at a constant load indicates that a constant load would provide constant current at maximum capacity. The diminishing charge causes decrease in the terminal voltage of the battery in accordance with the properties typically observed in a lead acid battery, resulting in a reduction in the electric current. Constant current means that the burden will draw constant current from the battery, resulting in a constant decrease in battery capacity.Due to the voltage decrease that is an inherent characteristic of lead acid batteries, a constant current cannot be maintained throughout the entyre discharge cycle. Figures 5.25 to Fig.5.28 demonstrate that, despite the fact that the battery discharge was initiated at a constant current rate, the curves decline rapidly after a certain period of time due to a drop in potential.

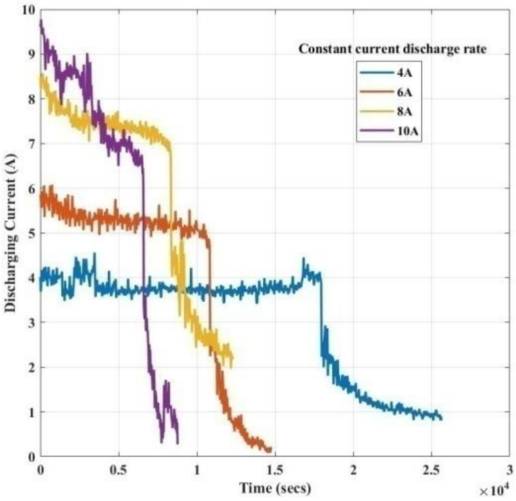

Fig.5. 28 Discharge cycles at various current rates

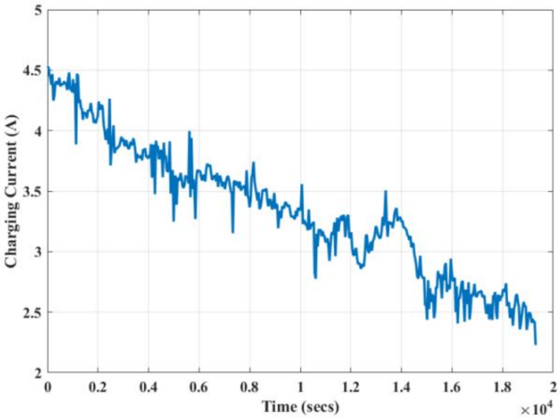

Fig.5.29 Curve showing the charge profile for a single cycle of operation

The charge profile for a single cycle of operation for the test lead acid battery has been depicted in Fig. 5.29. It is evident from the curve that at a rate of 0.1C, it takes approximately 5 hours for the battery to attain its state of full charge. The experiment was repeated at various other constant current rates. The Coulombic efficiency at various current rates has been manually determined and then projected in Fig.5.30 with the aid of Matlab's curve fitting tool.The curve demonstrates a decreasing trend of efficacy as the current increases. It indicates that the efficiency of lead acid batteries ranges between 80 and 90%. The State-of-Charge of the battery at a discharge rate of 10A over a single cycle is depicted in

Fig.5.31. Thus, it can be concluded that the proposed method is straightforward, generates satisfactory results, and provides a simple technique which can be used to determine both the coulombic efficiency and the SoC of a battery system. Researchers in the field of EV applications can easily use this method, as the efficiency and condition of charge are essential factors in determining range. When constructing an eco-routing navigation system, the obtained range can be applied to the calculation of energy consumption during a trip.

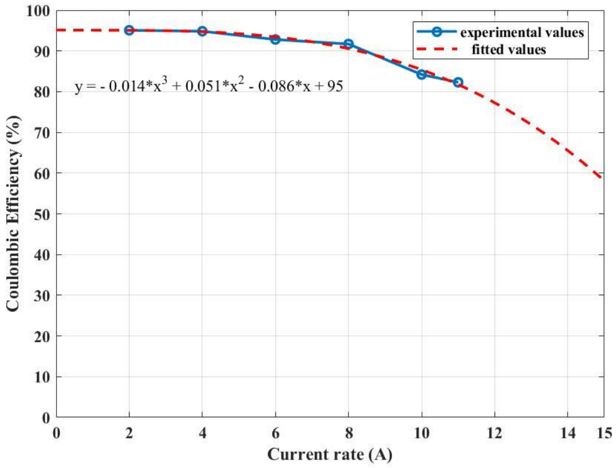

Fig.5.30 Curve depicting the coulombic efficiency at different current rates.

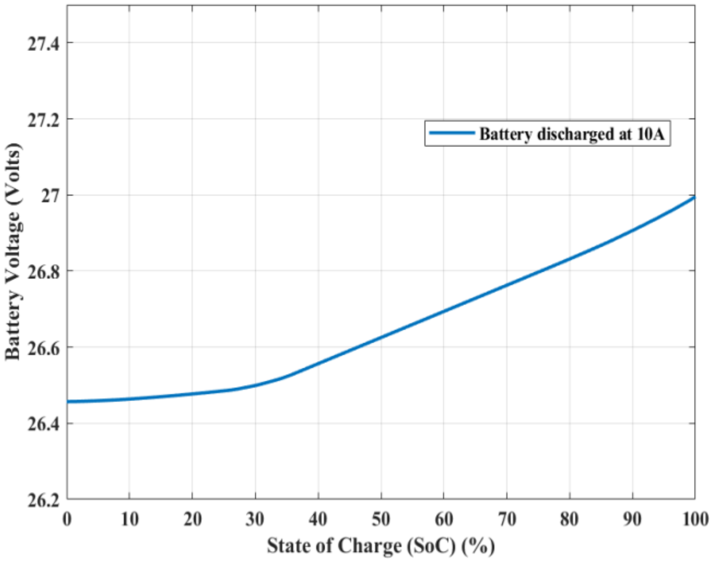

Fig.5. 31 The State of Charge of the test battery over one cycle of discharge

5.4. Conclusion

This chapter presents a study on batteries and their influence on electric vehicles, their energy usage, and eco-routing navigation. The different types of batteries used in EVs have been discussed, highlighting the merits as well as demerits of lead acid and lithium ion batteries in EVs. Various battery modelling approaches that are used to evaluate battery behaviour for onboard electric vehicle based applications have been studied. A motor-generator coupling technique has been devised and implemented for the extraction of battery parameters and the estimation of the coulombic efficiency of a battery that will be used in an EV test vehicle. The primary objective of this research work has been to develop a method for obtaining parameters such as current, Coulombic Efficiency and State of Charge for test batteries. In addition, a simplified battery model has been simulated, and modelling has been performed to demonstrate a comparative analysis of theoretical and experimentally obtained data. This method can be used to test any battery type before using it for a particular application. A 24V/26Ah lead acid battery was tested by continuously charging and discharging it for multiple cycles. The experiments were conducted by applying varying loads at constant current rates. In this experimentation, however, only the tangible aspects of batteries have been considered. Other external factors have been disregarded here. It can be seen that the results obtained are satisfactory and consistent with the existing theoretical data. The data for both discharge and charge can be observed and recorded in real time, which is an added benefit of the method. It has been observed that a 26Ah battery discharged at a constant current rate of 8 A took approximately 3.33 hours, which is consistent with theory. The utilisation of the Coulomb counting technique has been employed for the purpose of ascertaining the coulombic efficiency and state of charge of the battery. The obtained results demonstrate the effectiveness of the suggested approach in accurately estimating and analysing battery parameters, specifically the coulombic efficiency. The use of simple, cost effective components makes the setup user-friendly and great for research purposes. The Coulombic Efficiency degrades as the number of charge-discharge cycles increases. If the battery is discharged at moderate or low current rates, an efficiency of 90 to 92 percent can be achieved. CE is primarily determined by the discharge current rate. In order to create a system that is even more effective, the developed experimental apparatus must be modified in subsequent studies. In addition to the use of Coulombic Efficiency in the calculation of electric vehicle range, which is essential for determining energy consumption and eco-routes, additional research shall focus on the application of Coulombic Efficiency in the estimation of energy consumption and range of electric vehicles.

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