Challenges in battery pack design for electric vehicles with special emphasis on state-of-charge (SOC) estimation

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According to the International Energy Agency, there were more than two million electric vehicles (EVs) on the road at the start of 2017 [1]. The average size of a battery pack across hybrid, plug-in hybrid and battery electric vehicles is approximately 50 kWh. Considering that a single cylindrical lithium-ion cell typically contains 12 Wh, the net result is several billion cells currently in use as energy storage in EVs. Regardless of the chosen chemistry, that amount of energy has to be managed safely and reliably at a satisfactory level of performance. Addressing the challenges in battery pack design is essential to the success of EV technology and the most challenging aspect remains accurate state-of-charge (SOC) estimation [2].

Even though EVs only account for 0,2% of the total number of light-duty passenger vehicles at present, this share is expected to grow significantly [1]. With advances in research and improvements in mass production, batteries for EVs are becoming less costly such that Bloomberg predicts an EV to cost as much as its internal combustion equivalent by 2022 [3]. With the added appeal of tax exemptions and other economic incentives, it would seem that the cost of purchasing an electric vehicle might not be such a significant barrier to mass adoption in the near future [4].

One of the other significant barriers to purchasing a battery electric vehicle (BEV) is the possible distance the vehicle can travel before the battery pack requires a full recharge [4]. Battery "fuel gauging" has improved meaningfully over the past decade, but consumers still experience range anxiety. Reliable indication of the battery pack's remaining capacity is essential to the consumer and proper charge control cannot be achieved without accurate SOC information. Without proper charge control by the battery management system (BMS), the battery pack's performance suffers and its lifetime is reduced [5].

The aim here is to shed some much-needed light on an estimated quantity that the majority of consumers take as an accurate indication of a battery's remaining useful capacity. The true meaning of the term state-of-charge is explored and charge capacity is explained. An original approach to electromotive force characterisation from estimates of the electrolyte concentration in an electrochemical cell is also described. Preliminary experimental results from the application of this concentration-based approach for the purposes of open-circuit voltage prediction are presented. Other challenges in battery pack design such as cell matching, charge balancing and thermal management are briefly discussed.

Battery energy storage in electric vehicles

The term "battery pack" used here refers to the entire battery energy storage system and, in addition to the actual battery cells, includes the wiring, sensors, switches and integrated circuitry that comprise the BMS. The pack also includes components for thermal management which can range from a few fans to sophisticated liquid cooling systems such as those used in the Tesla Model S [6]. A mechanical structure is required to house the cells and the associated hardware and this structure can include holders, tubing, connectors, casings and even a packing material in between the individual cells. These cells are connected as modules and then stacked to complete the so-called "battery". The cells in a typical BEV are connected in parallel to increase the available current (I) as depicted in Fig. 1 (a) and then these modules are connected in series the achieve the desired operating voltage (V). Connecting the cells in series first, as depicted in Fig. 1 (b), followed by the modules in parallel is another possible configuration [7]. The resulting battery is an $m \times n$ matrix of cells, ranging from 10's to 1 000's of units depending on the chemistry and format [8].
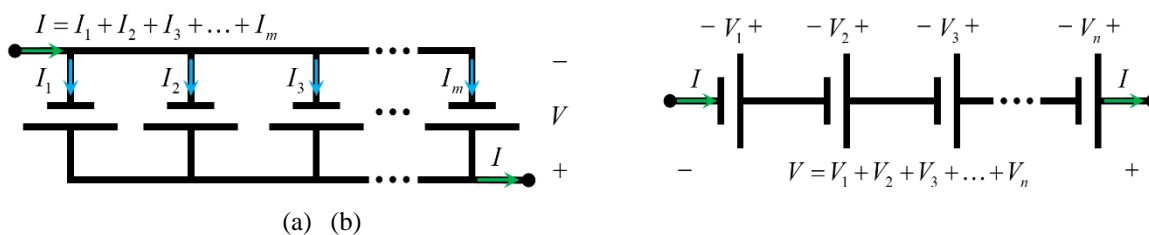

Fig. 1: Cells connected in (a) parallel and (b) series to obtain modules.

Even though a cell or battery is typically regarded as a constant DC voltage source in circuit schematics, this is hardly the case in reality. The BMS can be designed to charge or discharge the battery by constant current, constant voltage or constant power for a finite amount of time depending on source availability and load requirements. To illustrate the

complex nature of an individual cell, an experimental result from cell characterization efforts for the NWU's solar car is presented in Fig. 2. The measured voltage of a single 18 650 lithium-ion cell from Panasonic during various modes of operation at a constant temperature of $25°C$ can be seen. The cell is initially at rest followed by a constant-current discharge (CCD) until the minimum voltage (V_{min}) of 2,5 V is reached and the cell is deemed empty or at 0% SOC. The discharge is followed by a substantial rest period after which a constant-current charge (CCC) is applied. As soon as the cell reaches the maximum voltage (V_{max}) of 4,2 V, it enters a constant-voltage charging (CVC) phase until current absorption reaches a minimum of 70 mA. At this point in time, the cell is deemed fully charged or at 100% SOC. Even from this full cycle experiment, it should be clear that a battery cell is not a constant voltage source and its behavior is highly nonlinear.
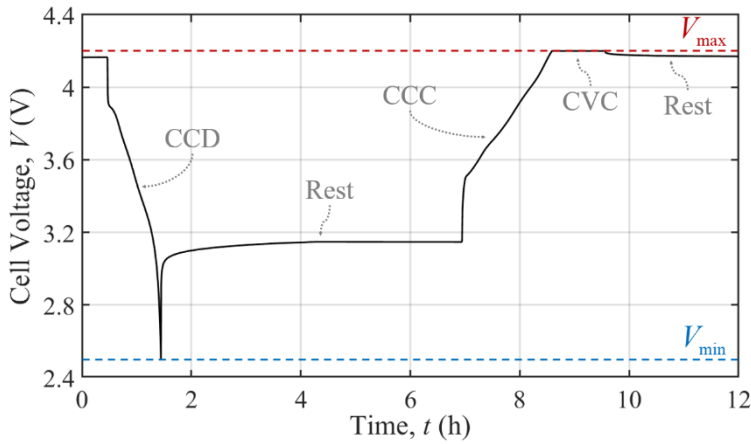

Fig. 2: Measured voltage of an 18650 lithium-ion cell during a full cycle at $25°C$.

Available capacity and state-of-charge (SOC)

The first noteworthy aspect regarding SOC is that it is not a measured quantity but a relative indication of a cell or battery's remaining useful capacity. The SOC is most simply calculated by a method known as Coulomb counting in which the applied current is integrated over time and then divided by a reference capacity, as shown in the following equation:

$$\text{SOC}(t_k) = \text{SOC}(t_0) + \frac{1}{Q_R} \int_{t_0}^{t_0+t_k} I(\tau)d\tau \tag{1}$$

where:

$\text{SOC}(t_k) = \text{SOC at time of interest, } t_k$
$\text{SOC}(t_0) = \text{SOC at start of calculation}$
$Q_R = \text{reference capacity in Ah}$
$I = \text{applied current in A}$

The BMS or charge controller faces significant difficulty in accurately determining the SOC if the reference capacity (Q_R) differs substantially from the cell or battery's available capacity. The rated capacity from the manufacturer's datasheet can be used but serious errors result because the actual capacity changes over time [9, 10]. In addition, any errors in current measurement will be amplified due to the integration operator in Eqn. (1). Another consideration is that of energy lost to side reactions: measurements would indicate that the current was absorbed by the cell but it is not available during a subsequent discharge. As a result, the SOC begins to drift over time and becomes useless if it is not periodically recalibrated [11].

One may very well ask why the current is used to indicate the remaining useful capacity of a cell if there are so many issues associated with it. The nonlinear nature of the cell is attributed to the various reactions taking place within and between the electrodes and electrolytes of the cell. The type of battery chemistry, such as lead-acid, is determined by the main reduction-oxidation (redox) reactions taking place at the interface between the electrode and the electrolyte, which is known as the electrochemical double-layer (EDL). The main redox reactions are associated with a specific voltage range and, as long as these reactions can be sustained, the cell delivers or absorbs current (I).

The EDL, where energy conversion takes place, is indicated in Fig. 3 (a) along with the other components of a typical cell during discharge. Ion transport across the separator is enabled by the electrolyte and electron transfer takes place at the EDL. The movement of electrons via the external conductive pathway is responsible for the observed current (I) with the current direction always opposite to that of the electrons [12]. Electrons in the conductive band of an electrode move in response to the electric field established by the electrode potentials. The electrons move in the reverse direction during charge as illustrated in Fig. 3 (b). Notice that even though the positive and negative terminals do not change, the cathode and anode switch because the reactions take place in the opposite direction during charge. Another important observation is the electron pathway indicated in Fig. 3 (b): the electrons are not conducted within the electrolyte but 'hitch a ride' with the ions. An internal conductive pathway for the electrons would imply an internal short-circuit and is to be avoided at all cost.
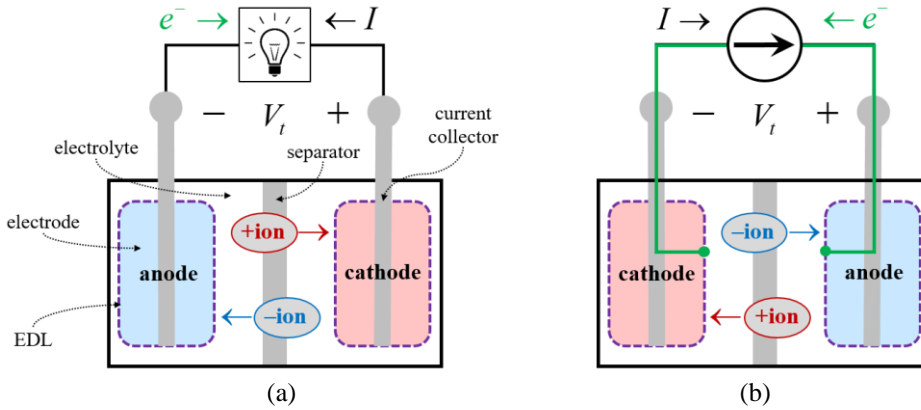

(a)   (b)

Fig. 3: Cell operation during (a) discharge with EDL indicated and (b) charge with electron pathway indicated.

The question related to a cell's available capacity now becomes: how long can ion transport within the electrolyte and electron transfer at the EDL continue to sustain the observed current within the specified voltage range? The energy conversion stops when either the active material in the electrodes or ion concentration in the electrolyte becomes depleted. Even though the active surface area of an electrode is much larger than its geometric area because of the porous nature of the electrode material, passivation also slows the energy conversion. Obtaining an accurate estimate of the remaining useful capacity lies in making the most of the available current, voltage and temperature measurements.

Electromotive force and open-circuit voltage (OCV)

The maximum electric work (w_{max}) possible by a cell based on a known redox reaction is the product of electric charge and the cell's electromotive force (E) as given by the following equation:

$$w_{max} = nFE \tag{2}$$

where:

n = number of electrons involved in the reaction
F = Faraday constant of 96 485 C/mol
E = electromotive force (EMF) in V

Eqn. (2) assumes ideal conditions wherein no heat is generated and no energy is lost to the environment [13]. The EMF is related to the voltage measured at the terminals of the cell during operation using:

$$E = V_t - I \cdot R_{int} \tag{3}$$

where:

V_t = terminal voltage in V
I = applied current in A
R_{int} = internal resistance in Ω

Measuring the terminal voltage and applied current during operation is a relatively simple task. The internal resistance varies with SOC, lifetime and temperature and cannot be determined as easily [14]. Severely passivated electrodes will have a large internal resistance because the active surface area has been significantly reduced.

In most applications, the EMF is obtained from OCV measurements if the cell has been at rest for a sufficiently long time and stable measurements can be made. It is also important to note that the OCV of a single cell can only be measured if it is not connected in parallel with other cells [7]. The measured OCV as an estimate of the EMF is useful in online applications because there is a strong relationship between the EMF and SOC [11]. Some BMS algorithms make use of this relationship to periodically recalibrate the SOC using the EMF in a method known as voltage lookup or voltage-based estimation [10].

Electrolyte concentration for EMF characterization

The Nernst equation enables the calculation of a cell's EMF, at a temperature of interest, T, as illustrated in the following equation:

$$E = E^\circ - \frac{RT}{nF} \ln Q \tag{4}$$

where:

E° = the cell's standard potential at T_{ref} = 298,15 K (25°C)

R = the universal gas constant of 8,3144 J/(mol·K)

T = the temperature of interest in K

n = number of electrons involved in the reaction

F = Faraday constant of 96 485 C/mol

Q = the reaction quotient

The reaction quotient (Q) depends on the various species concentrations and their associated thermodynamic activity at different temperatures. This quotient is sometimes specified simply in terms of the concentrations of the reactants and products [12]. Since these concentrations change as the cell charges and discharges, the reaction quotient is the only unknown variable in Eqn. (4) not easily obtained from a commercially available cell. Consider Fig. 4 depicting the simulated electrolyte concentration in the different regions of a lead-acid cell during a high-rate discharge. A valve-regulated lead-acid (VRLA) cell with an absorbed glass-mat (AGM) separator was simulated in COMSOL Multiphysics using a previously validated electrochemical model [15]. The concentration is completely uniform across the cell at the start of discharge when $t = 0$ s. As the discharge proceeds, the concentration decreases quicker in the positive electrode (POS) than the negative electrode (NEG). Toward the end-of-discharge (EOD) at $t = 80$ s, the concentration is very non-uniform across the cell.
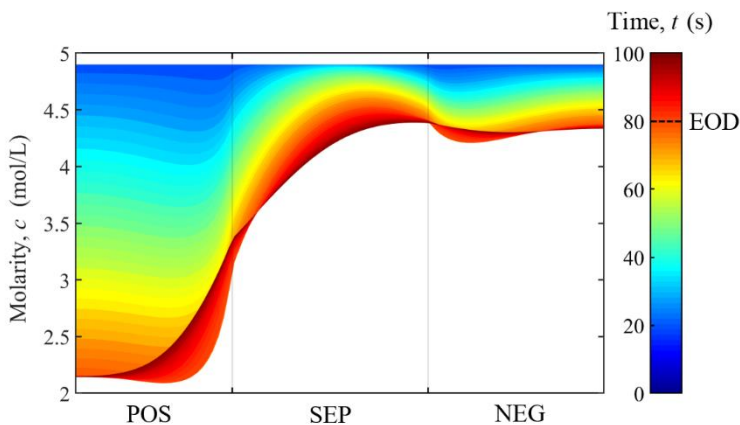

Fig. 4: Simulated concentration gradients in a VRLA cell with AGM separator during a high-rate discharge.

Note how the concentration seems to visually 'fold back' on itself as the cell enters a 20-second rest period. This behavior explains the required rest period before stable OCV measurements can be made: the concentration has to homogenize across the cell before the OCV becomes fully relaxed. The strong relationships between the work done by the cell, the EMF and the electrolyte concentration inspired a method for EMF characterization based on estimates of the concentration.

The electrolyte concentration in mol/kg (molality) was estimated from stable OCV measurements using the Nernst equation in Eqn. (4). These molality estimates were then used to map the amount of work done by the cell to changes in the molality and obtain the molality at a time of interest (t_k) using the following equation:

$$m(t_k) = m_0 + [(m_{EOD} - m_0) \cdot w(t_k)] / w_{EOD} \qquad (5)$$

where:

$m(t_k)$ = molality at time of interest, t_k

m_0 = molality at start of calculation

m_{EOD} = molality at EOD

$w(t_k)$ = work done by cell at time of interest, t_k

w_{EOD} = work done by cell at EOD

The resulting molality during operation, $m(t_k)$, can then be used to estimate the EMF during operation. The voltage curves in Fig. 5 illustrate how well this concentration-based method performs. The terminal voltage (V_t) of a lead-acid cell during discharge, rest and charge is shown along with stable OCV measurements indicated by E^*. The dashed curve in red is the estimated EMF based on the electrolyte concentration, or $E(m)$. Even though these results are from a preliminary investigation, they indicate that other ways of estimating the available capacity of a cell might be possible.
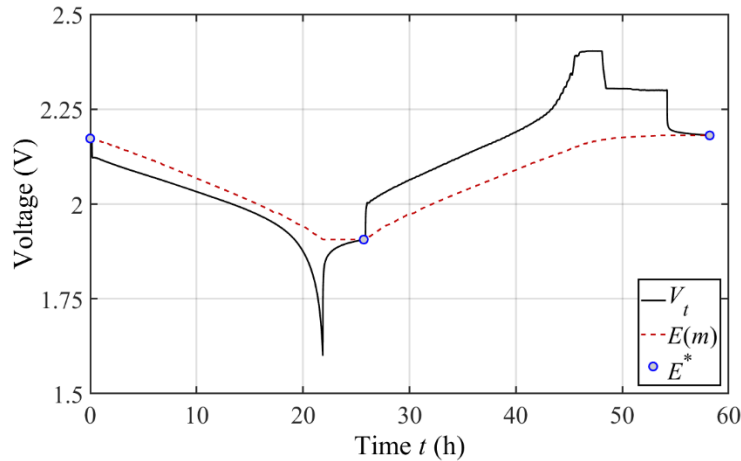

Fig. 5: Estimated EMF during operation of a lead-acid cell from the concentration-based method.

The concentration-based method's initial aim was to rely on something other than Coulomb counting for the purposes of capacity estimation and attempt more of a white-box approach. Other SOC estimation methods typically rely on black-box approaches and include adaptive techniques such as Kalman filtering and neural networks [2]. These methods can offer a sufficient compromise in terms of accuracy and computational effort depending on the intended application. Capacity estimation methods which require more computational effort and have limited online implementation are those based on electrochemical models but they are more accurate than those using equivalent circuit models [10]. Recent efforts for capacity estimation aim to incorporate state-of-health information to achieve a BMS that even takes aging into account [16].

Other challenges in battery pack design

As clearly illustrated here, a single battery cell exhibits complex behavior and should be regarded as a highly nonlinear energy source. Controlling thousands of these complex units connected together as the battery for an electric vehicle requires the use of battery management hardware. Charge control is made easier by cell matching and charge balancing. Cell matching is typically performed after initial screening but before pack assembly by characterizing the individual cells according to their reference capacity and internal resistance. The purpose of cell matching is to ensure that cell-to-cell variations are as small as possible and that the pack is well balanced at the start of service.

Consider multiple cells in parallel all with the same internal resistance but a single cell is at a lower SOC than the rest of the cells. Because the cells are connected in parallel, they benefit from a natural balancing effect when not in use: the cell with the lower SOC can draw current from cells with a higher SOC [7]. If these parallel-connected cells started with

notable differences in their internal resistance as well, current division between them would be uneven and some cells would discharge/charge more than other cells. Additionally, the parallel configuration does not allow for cell-level voltage measurements unless the cells are disconnected from each other. The risk of over-charging or over-discharging increases and the pack's safety and reliability cannot be guaranteed [14].

If a string of cells connected in series were evenly matched and subjected to the exact same operating conditions, the cells should remain balanced because the current through each is the same [2]. Even with strict quality controls and automated cell manufacturing, one cell is always slightly different from the next cell with a unique state-of-health. A series string can also become unbalanced if parasitic loads from the BMS or other electronics are not evenly distributed across the cells or modules.

Charge balancing aims to minimize SOC differences and, consequently, EMF differences between cells throughout the pack's lifetime. A definite design trade-off occurs when considering charge balancing in large battery packs. Passive balancing is a simpler method wherein cells at a higher SOC are discharged through resistive elements to match them with cells at a lower SOC but that energy is lost. Active balancing aims to redistribute the excess charge in cells with a higher SOC to those cells with a lower SOC by switching electronics which is more complicated [17]. The hardware required to achieve charge balancing adds to the weight and complexity of the battery pack but improves its safety and reliability [7].

A battery cell's lifetime and performance are greatly influenced by temperature because the electrochemical reactions are temperature dependent. Internal exothermic reactions generate heat and an elevated ambient temperature also plays a significant role by accelerating these reactions. Excessively large currents, either from incorrect operation or an internal/external short-circuit, would result in excessively large reaction rates and an overheated cell [17]. While some battery chemistries have built-in protective circuitry to interrupt current to a cell, the BMS can also apply an external interruption to the module or pack. The aim is to avoid the propagation of thermal runaway throughout the entire pack by dissipating the excess heat as quickly as possible. An effective thermal management strategy cannot be an afterthought in battery pack design but should be regarded as an essential element toward improving safety in an EV application [6].

Conclusions

With a clear understanding of the smallest unit in a battery pack, existing methods for SOC estimation can be improved. Addressing the challenges in battery pack design can only increase the safety, reliability and performance of battery energy storage in EV applications. Along with advances in fundamental battery research, addressing the challenges in battery pack design for electric vehicles can aid in accelerating electric vehicle adoption. The power of battery energy storage lies in enabling the electric vehicle as a disruptive technology.

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