Analysis of battery management system issues in electric vehicles

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Abstract. Battery technology has dramatically advanced over a decade and many high performance batteries are being developed. Electric vehicles (EV) require high power batteries with suitable battery management systems (BMS) for safe and reliable operations. Intention of this paper is to discuss about the batteries used in electric vehicles and the key issues of battery management systems and to compare the Lithium ion (Li-ion) battery & Nickel metal hydride battery in terms of aging and effect of temperature using their state of charge (SOC) and open circuit voltage (OCV).

1. Introduction
Electric vehicles are under constant research area and researchers keep working on it for reduced fuel usage and to reduce CO₂ emission. EVs are classified as hybrid electric vehicles and battery electric vehicles. Batteries play a major role in smooth running of EVs. High power batteries require proper care and they should be sensed for their voltage, current and power. Improper operation of batteries like over charge, over discharge, over current and extreme temperature might throw problems to the user. Hence proper BMS helps in overcoming these issues and provides a safety drive for electric vehicles.

Key technologies in the BMS of EV include battery modelling, state estimation, charging and discharging. A good BMS should safely protect the driver/operator by detecting unsafe operating conditions, protecting the cells from damage in failure cases, prolongs the life of battery in normal operating region and should inform the user about the battery details and its status of operation.[3] This paper also explains about the different batteries and their electrochemistry. A battery has to be charged, discharged and its parameters are to be estimated well for its good maintenance. The measurable variables such as voltage, current, temperature that varies with state of charge are required for accurate and robust SOC estimation. This paper explains the variation of OCV and internal resistance of the battery at different SOC of Lithium ion battery and NiMH battery. Variation of its internal resistance curve at room temperature gives us the need for modelling a battery based on thermal behaviour.

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2. Battery types

There are two different categories of battery cells namely Primary cells and Secondary cells. In case of primary cells the electrochemical reaction that occurs during the discharge is not reversible. If we try to recharge a primary battery, the compounds that have been formed during discharge will not recombine into the original compounds that were present before discharge and therefore it’s not rechargeable. This is the principle reason that primary cells are meant for only one time use. Secondary cells are special in the sense that their chemical reaction has been designed in such a way that it is completely reversible. The original chemical compounds that are changed during discharge can actually be reconstituted into its original form by the application of external potential between the electrodes that inject energy into the cell. Secondary cells can be discharged and recharged infinite times but its life is limited by degradation of the cells.

Some popular types of batteries are Dry cell, Alkaline cell, lithium-ion (Li-ion), lead-acid (PbA), Nickel-Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Nickel Zinc, Zinc air. as shown in Table 1 with their electrochemistry.

| S.No | Electrochemistry | Nominal voltage | Negative electrode | Positive electrode | Electrolyte |
|------|------------------|------------------|--------------------|--------------------|-------------|
| 1    | Lead acid        | 2.1V             | Pb                 | PbO₂               | H₂SO₄       |
| 2    | Dry cell         | 1.6V             | Zn                 | MnO₂               | ZnCl₂       |
| 3    | Alkaline         | 1.5V             | Zn                 | MnO₂               | KOH         |
| 4    | Nickel cadmium   | 1.35V            | Cd                 | NiO₂               | KOH         |
| 5    | Nickel Zinc      | 1.73V            | Zn                 | NiO₂               | KOH         |
| 6    | Zinc air         | 1.65V            | Zn                 | O₂                 | KOH         |
| 7    | Nickel metal Hydride | 1.2V | H₂ in form of metal hydride | Ni(OH)₂ | KOH |
| 8    | Lithium ion      | 3.7V             | Graphite           | LFP, LMO, LCO      | LiPF₆       |

Among the above different types of batteries, NiMH and Li-ion batteries are highly preferred. NiMH has higher specific energy, energy density than cadmium electrode. They have higher capacity and longer life than NiCd batteries. Since it is free of cadmium they are considered as an environment friendly battery. The magic of NiMH cells is the negative electrode which is a rare earth hydrogen absorbing metal alloy. There is no electro chemical reaction taking place in the negative electrode that changes its structure when hydrogen goes in and comes out of the electrode.

The Li-ion cells also allow intercalation of lithium ions into crystalline lattice of graphite without changing its crystalline structure. Li-ion batteries have higher open circuit voltage which reduces the number of cells in a battery pack. Higher energy density makes the battery pack compact and high specific energy lightens the overall weight of the vehicle. They can be operated in a wide temperature range without decreasing its lifetime. Li-ion batteries can be charged and discharged at higher C-rate at normal operating conditions, so that a small battery pack can meet peak power requirements and absorb most regenerative energy.

| S.NO | REQUIREMENT | NiMH | Li-ion |
|------|-------------|------|--------|
| 1    | Specific energy | 40-80Wh/Kg | 130-200Wh/Kg |
| 2    | Energy density | 90-160Wh/L | 180-320Wh/L |
| 3    | Specific power | 900-1600W/Kg | 1200-4000W/Kg |
| 4    | Charge/discharge efficiency | 80-95% | 85-96% |
| 5    | Self-discharge rate | 8-15% month | <5% month |
| 6    | Cycle durability | 800-1200 cycles | 1500-2000 cycles |
| 7    | Nominal cell voltage | ≈1.2V | ≈3.7V |
3. Battery modelling
Battery system consists of battery cells. Depending on the requirement of output voltage, power and energy capacity for an EV, a battery pack contains many cells connected in series or parallel or both. Battery operation and its input-output parameters can be studied by modelling the battery. Proper model of the battery is required for a good BMS design; control and optimization. There are several methods available to model a battery, and the most widely used are electric model, thermal model and electro-thermal model.

3.1. Battery electric model
Electro-chemical model, reduced order electric model, equivalent circuit model, Data driven model are the types of battery electric model. Among these different models, the equivalent circuit model is widely adopted has the model structure is simple with less number of model parameters. In the equivalent circuit model battery electric behaviours can be studied by a combination of circuit components such as resistors, capacitors, voltage sources as given below.

![Battery model Equivalent circuit](image)

**Figure 1. Battery model Equivalent circuit**

The resistors and capacitors are related to charge transfer or diffusion processes. Model order is denoted by the number of RC networks as given by Kailong LIU et al[1]. First and second order models are popular and higher orders are of less importance. This model has better dynamic performance especially for State-Of-Charge (SOC) and power estimations. The other models are not discussed here.

From the above figure according to KVL

\[ V_t = V_{OC} + V_{ohm} + V_{dyn} \]  

\[ V_{OCcell} = V_0 - \frac{R_g T}{n_e F} \ln(Q) \]  

\[ Q = f(SOC) \]  

\[ V_{ohm} = I_r R_{ohm} = I_r R_{ohm}(SOC,T) \]  

\[ V_{dyn} = I_{R_{dyn}} R_{dyn}(SOC,T) \]  

\[ I_{cdyn} = C_{dyn} (SOC,T) \frac{dV_{dyn}}{dt} \]  

Terminal current \( I_t = I_{R_{dyn}} + I_{cdyn} \)

Where \( V_t \) is terminal voltage in volts, \( V_{ohm} \) is the voltage across \( R_{ohm} \), \( V_{dyn} \) is dynamic voltage across the resistor. \( V_{OC} \) is the open circuit voltage. \( V_0 \) is no load voltage, \( R_{dyn} \) is dynamic resistance. \( T \) is the battery temperature. \( F \) is faraday constant, \( n_e \) is the number of electron transferred in cell reaction and \( R_g \) is universal gas constant.[5]
Dynamic voltage $V_{dyn}$ can be described by the differential equation

$$
\frac{dV_{dyn}}{dt} + \frac{V_{dyn}}{R(SOC,T) + C_{dyn}(SOC,T)} = \frac{1}{C_{dyn}(SOC,T)}
$$

Overall differential equation of electrical circuit

$$
\frac{dV_{l}}{dt} + \frac{V_{l}}{C_{dyn} R_{dyn}} = \frac{R_{ohm} \cdot \frac{di}{dt} + \frac{R_{dyn} + R_{ohm}}{R_{dyn} + C_{dyn}} \cdot I_{t} + \frac{V_{oc}}{R_{dyn} + C_{dyn}}}{R_{dyn} + C_{dyn}}
$$

3.2. SOC calculations

SOC of a battery gives the percentage of available amount of energy over its maximum achievable amount.

For EV System Performance, Analysis and Simulation as well as design battery SOC calculation,

$$
SOC(t_{i}) = SOC(i_{0}) + \frac{1}{CAP_{Ah}} \int_{t_{i}}^{t_{f}} I(t) \eta_{batt}(SOC,T,SignI(t)) dt
$$

Where $\eta_{batt}$ is the columbic efficiency of the battery, $CAP_{Ah}$ is the capacity of battery in ampere-hours.

3.3. Modelling thermal behaviour

Heat generated by the battery is the heat generated by the resistors in the electric circuit model.

Heat generated by the resistors is

$$H_{gen} = H_{Rohm} + H_{dynamic} + H_{react} \text{ (W)}$$

Ohmic resistance heat

$$H_{Rohm} = |I| \cdot |V_{ohm}| = I^{2} R_{ohm}(SOC,T) \text{ (W)}$$

Dynamic heat given by

$$H_{dynamic} = |I| \cdot |V_{dyn}| = |I| \cdot \int_{t_{i}}^{t_{f}} \left[ \frac{R_{dyn}}{C_{dyn}(SOC,T)} \cdot \frac{V_{dyn}(t)}{SOC(T)} \right] \cdot \frac{V_{dyn}(t)}{SOC(T)} \cdot dt$$

At initial condition $V_{dyn}(0) = 0$. The reaction heat is given by

$$H_{react} = \frac{S \cdot I \cdot \eta_{batt} \cdot T}{F}$$

Where $\Delta S$ is delta entropy of the reaction(J/mol-K), $F$ is faraday constant=96,487 C/mol

Dissipated heat is

$$H_{dissipated} = (T_{coolant} - T) h_{bat} \text{ (W)}$$

Battery temperature is given by

$$T(t) = T(t_{i}) + \int_{t_{i}}^{t} \left[ \frac{H_{gen} + H_{dissipated}}{C_{bat} M} \right] dt$$

where $T_{coolant}$ is the temperature of coolant(K), $h_{bat}$ is heat transfer coefficient of battery (W/K), $T(t_{i})$ is initial temperature of battery. Using the above equations a EV system battery electrical model can be implemented as given below.
3.4. Comparison of SOC, OCV, temperature

SOC is used to determine the battery capacity. There are several methods available to determine SOC. The measurement of OCV is a voltage based SOC determination [16]. OCV can be measured without load and this method is suitable for estimating initial SOC. OCV is the terminal voltage of the battery at no load and the battery is kept at rest for one hour. In this experiment conducted, a 400 V, 100Kw power capacity and 20 Kw energy capacity Amaron single NiMH battery cell is selected. This experiment is done at 20° centigrade. The OCV measurement for 100% SOC is done under the charging mode with a charging current of 1C. Experiment is started at the initial battery voltage of 0.12V. For every increase in 1% charge the voltage is noted. After 100% reach of SOC of battery at 1.2V, the battery was given a rest of 1 hr. There is no charging and discharging process for this 1 hr. There is no significant change in OCV. SOC and OCV plot is given below in fig 3.

Similarly a cylindrical LFP battery with the same rating of 400V, 100 Kw power capacity and 20 Kw energy capacity is selected. Using voltage based SOC determination OCV is noted. The experiment is started at initial battery voltage of 3.15V and at final 100% SOC capacity battery reached 3.46V. 1 hour rest period is given. There is no significant drop in the voltage of the battery. SOC and OCV plot is given below in fig 3.

Using linear regression the curve fitting is done and the 4th degree polynomial equation is obtained as given below

4th degree LFP OCV $y = 8.709e-10x^4 + 6.305e-07x^3 - 0.0001258x^2 + 0.007891x + 3.163$

4th degree NiMH OCV : $y = -3.698e-08x^4 + 1.005e-05x^3 - 0.0009576x^2 + 0.04174x + 0.2489$

Figure 3. comparison Plot of SOC and OCV for LFP and NiMH

The coefficient of determination gives the goodness of curve fit with strong effect size for both LFP and NiMH. The Root Mean Square error RMSE gives the residual measure of farness of data points from the regression line.

Table 3: $R^2$ and RMSE for batteries in comparison

| S.no | LFP    | NiMH   |
|------|--------|--------|
| $R^2$| 0.9659 | 0.9728 |
| RMSE | 0.1012 | 0.3676 |
The values of RMSE are very less and had proven that data is around the line of best fit. Variation of internal resistance at different SOC is also measured, the dynamic resistance as given in the battery model. As shown in fig 4 for cylindrical LFP battery at initial SOC the internal resistance is 3.13Ω. For every change in SOC the internal resistance is measured and at 100% capacity of SOC the internal resistance for LFP is 2.37Ω. With high resistance the battery takes less current to charge and there is a slow charging. With battery SOC increasing it is seen that the resistance decreases with increasing charging current so that battery can be charged to required voltage. After 80% SOC is reached the internal resistance again increases since the battery voltage would have sufficiently reached the required voltage. In NiMH batteries the dynamic resistance is low and minor increase in resistance is seen at 100%SOC as shown in figure 4.

![SOC vs Internal Resistance](image)

**Figure 4.** comparison Plot of SOC and internal resistance for LFP and NiMH

### 4. Conclusions

Comparing the graph of fig 3 of SOC and OCV curve LFP has high voltage and is of high preference over NiMH. Cylindrical LFP is of high choice because they are easy to manufacture The major drawback of LiFePO$_4$–LFP batteries is the super flat slope of OCV and SOC graph as seen above, that makes SOC estimation and balancing cell among the battery system challenging. Batteries need to have high energy density, low internal resistance and long cycle and calendar life. Hence well trained battery model together with suitable estimation methods can be adopted to achieve independent or joint state estimation of battery SOC or internal temperature along with their dynamic resistance. The research work in the field of battery charging estimation along with temperature management is needed as Lithium batteries get easily heated up which reduces the life of batteries. Hence other chemical equivalent battery materials are needed to be considered to prolong battery usage to maximum

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Authors’ background

Note:

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