Simplified Modelling of a Battery Parameters and Application in Electric Vehicle Battery Charging Based on State of Power (SoP) and State of Energy (SoE)

Subhadeep Bhattacharya [1)] and Pavol Bauer [2)]
[1)] McGill University, Montreal, Canada, e-mail: *subhadeep.bhattacharya@mail.mcgill.ca*
[2)] Delft University of Technology, Delft, The Netherlands, e-mail: *P.Bauer@tudelft.nl*

Abstract — **Estimation of equivalent circuit parameters and open circuit voltage of a battery to predict its state is important for electric vehicle (EV) applications. There is a need to measure the open circuit voltage as accurately as possible as it mirrors the state-of-charge (SoC) of the battery. As calculation of the SoC by integrating the amount of current going in or out of the battery is inaccurate and requires post-processing, this investigation presents one different way to calculate the open circuit voltage and thus the state of charge while the battery is being used. This paper also presents an analytical model of the state of an EV battery pack with the concept of State of Power (SoP) and State of Energy (SoE). These figures of merits help the user to determine how far a battery pack can be used in terms of the vehicle range and acceleration/deceleration capability. LiFePo4 cells were used as the type of Li-ion battery in this investigation. This paper investigates these aspects with the help of vehicle and battery data obtained experimentally and in laboratory environment. The simulation results have been compared and validated against the experimentally obtained results.**

Keywords — battery modeling, electric vehicle, State-of-Power (SoP), State-of-Energy (SoE), SoC Estimation

I. Introduction

The behavior of the electric battery within an electric vehicle presents many challenges and is at the forefront of the future transportation energy research. Large investments and R&D efforts [1] [2] were made to improve the performance, efficiency and reliability of the batteries. Past researches [3] show that more investigations need to be done to improve the energy efficiency of the entire EV system and charging infrastructures need to be implemented for proper usage of the battery. Even though lead-acid and nickel metal hydride batteries still dominate in the cell market share, most of the current research is focused on lithium-ion battery technology. When several of these cells are used in an electric vehicle, they present challenge to operate them safely as an individual unit and as a complete battery.

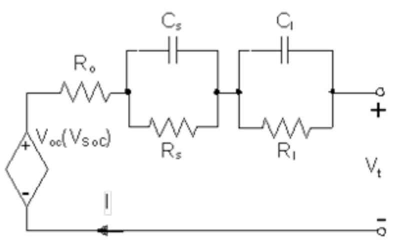

Fig. 1. Battery model.

To analyze properly the behavior of an electric vehicle (EV) with a LiFePo4 battery pack, it is very important to look at its behavior under various operating conditions. In [3-5], the behavior of a LiFePo4 battery was tested experimentally in different operating conditions. It was shown in the analysis [6-14] that the battery behaves very differently for different operating temperature and state-of-charge. In temperature below 273 K, lithium-ion batteries behave differently due to lithium-plating effect as shown in [15-16]. This may cause irreversible changes in the battery. In temperatures above 323 K, an initial increase in the capacity of the battery due to faster diffusion process eventually causes more degradation in the battery due to elevated temperature. Also, as reported in [3,5], for different state-of-charges, batteries behave differently due to changes in types of chemical processes going inside the battery. All these processes react differently towards change in temperature and state-of-charge. Thus, modeling of those processes is a significant challenge to properly predict and maintain a healthy life-cycle of the battery pack. This drive different modeling approaches [12] to estimate battery parameters. Now, due to non-linear behaviors of the battery, different approaches to model the battery parameters often produce complex equations which may not be necessarily accurate due to errors in parameter estimation for different operating conditions. So, in this investigation, simplified equations for battery parameters were included [8]. While doing so, it was assumed that the battery is properly monitored and controlled with a battery management system (BMS) and the user(s) will be notified about the proper usage of the battery [22]. The results from the analytical study were compared and validated with the experimental results obtained from testing a LiFePO4 battery and an electric vehicle under different operating conditions.

The parameter estimation techniques are dependent on proper measurement of temperature and state-of-charges of the battery. Measurement of the state-of-charge while vehicle is driving is a challenging task as calculation of

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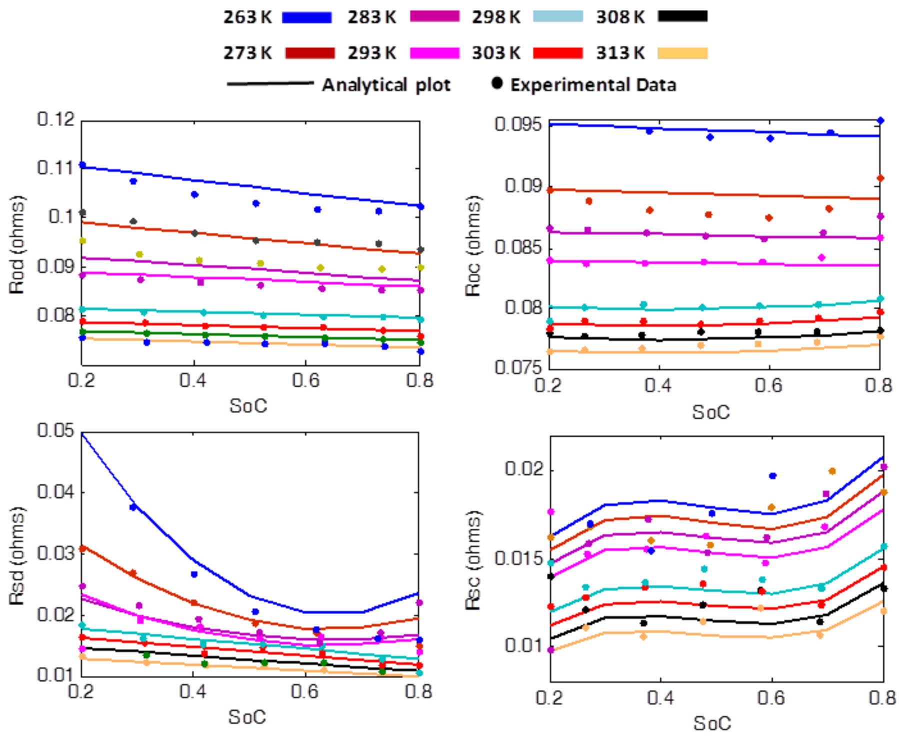

Fig. 2. Battery parameters w.r.t change in SoC (temperature increases from up (263K) towards down (313 K)).

charge replenished or depleted does not necessarily mirror the state-of-charge of the battery [4, 19]. So, in this paper, the online estimation of the state-of-charge with the information of current and voltage of the battery was investigated.

Also, this paper presents an analytical analysis to predict the State of Power (SoP) and State of Energy (SoE) of the battery along with the simplified battery model. The goal of this work is to develop proper analytical models with realistic battery electrical and thermal models that allow to quickly predict the power range capability of a battery pack with general configurations and to predict the time required to charge and discharge the battery along with the remaining range of the battery pack.

Section II of the paper deals with the modeling of a battery pack with equivalent circuit equations with analysis of experimental values. Section III discusses online SoC estimation technique. Section IV and V define the State-of Power (SoP) and State of Energy (SoE) of the battery. Section V discusses the simulation results with effect of different configurations of the battery pack.

II. Modeling Battery Parameters

In [1-3] there was extensive discussion of how to model the behavior of a battery used in automotive applications. In [1], the equations which correspond to different impedances of the battery equivalent circuit (Fig. 1) are too complex to handle with.

Also, as the battery is modelled for an electric vehicle performance, several assumptions can be made if one tries to simplify the model. Those are:

- The battery will not be charged beyond SoC 0.8 most of the time.
- The battery will not get discharged beyond SoC 0.2.

So, the impedances can be modelled within the working SoC range 0.2-0.8 as the Li-ion battery behaves best while working in the mid SoC range [1]. In Fig. 1, the open circuit voltage (Voc) is dependent on SoC of the battery. Ro is the ohmic resistance of the battery which includes electrolyte, electrode and surface layer resistance of the battery. Rs and Cs represent the charge transfer resistance and double layer capacitance of the battery. Rl and Cl models the diffusion phenomena in the battery. In Figs. 2, 3 the variations of different impedances of the equivalent circuit with respect to the SoC and ambient temperatures are shown based on experimentally obtained data. The resistances Roc and Rod (where subscript c and d signify charging and discharging scenarios) have a negative temperature coefficient. As temperature increases, lithium ions diffuse faster, which increases the current flow. This phenomenon initially decreases the resistance Roc (Rod) with the rise of temperature, which also accounts for an initial increase of the battery capacity. With time, due to elevated temperature, the battery starts to degrade faster and loses its available capacity gradually.

It can also be seen from Fig. 2 that for each circuit parameter dependency on SoC is different for charging and discharging. For most of the parameters, while charging, with increasing SoC, resistances (Ro, Rs, and Rl) increase. While discharging, the opposite happens. It may be due to the influence of different electrodes while charging and discharging. During charging, the limiting electrode is the positive one and while discharging, the negative electrode limits the charge transfer and intercalation process. So, while discharging, in lower SoC, corresponding battery resistances are higher and while charging, in higher SoC, resistances are higher. One can notice that in the SoC range 0.3-0.7, the charging, discharging resistances (Roc, Rod) are almost identical in nature and magnitude. So, if the user of the vehicle

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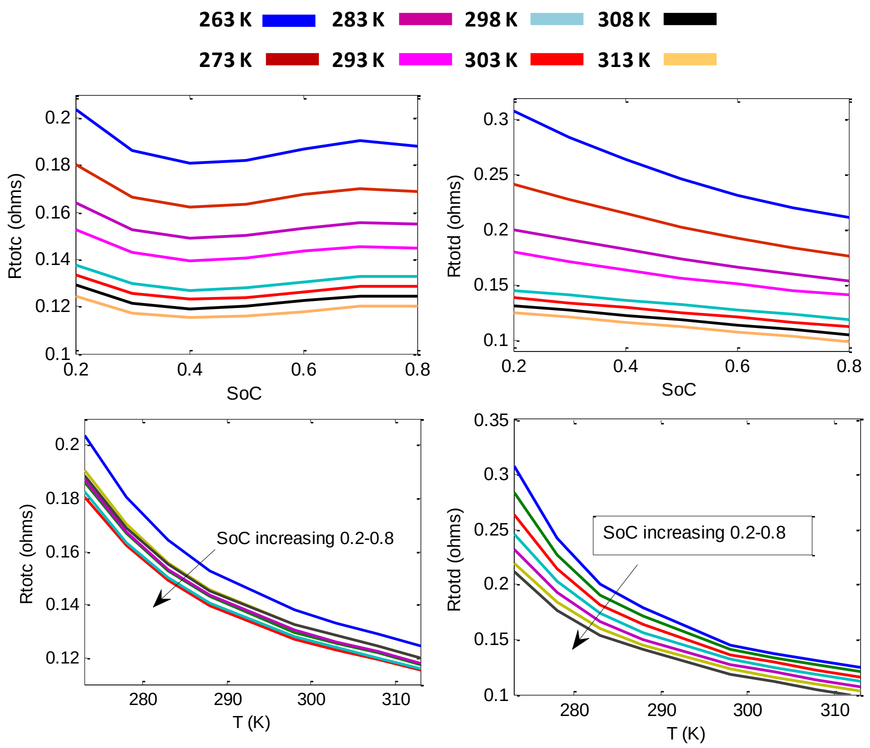

Fig. 3. Total resistances w.r.t Temperature and SoC (temperature increases from up (263K) towards down (313 K)).

decides to use the battery in that working range, we can have only the state-of-charge dependent equation for each circuit parameter for both charge-discharge scenarios.

In Fig. 3, the variations of the total resistances and different time constants (which determines how the battery will behave in frequent charge-discharge cycles) of the battery w.r.t SoC are shown. The total resistance of the battery is the summation of three different resistances (Ro, Rs, and Rl) as shown in Fig. 1. The total resistance of the battery while charging and discharging remains almost constant over the entire working range of SoC.

Based on the analysis and experimentally obtained data points (Figs. 2-3), parametric equations corresponding to different impedances of the battery were simplified and shown in Tab. 1. The parameters having 'd' as subscript are for discharge behavior of the battery and 'c' for charging scenario. The battery parameters can also be expressed in terms of the time constants associated with the circuit parameters in the charging-discharging scenario. Compared to [1], the new equations give identical results while using that in the model described in [1]. Also, when fitted with the data points got in the experiments, they show good fitting characteristic, as seen in Fig. 2. In [3-6], [17-18] there were discussions about how a battery will behave in different driving condition, namely temperature, remaining charges in the battery and driving patterns. In our work, we have found the available capacity of the battery under different working temperature and initial battery charges.

TABLE I.
BATTERY PARAMETER EQUATIONS

Parameter	Equation
R_{od}	$(-0.00244 * \mathrm{SoC} + 0.06247) * e^{(10.14/(T-260.8))}$
R_{oc}	$(3.146e^{-3} * \mathrm{SoC}^2 - 2.524e^{-3} * \mathrm{SoC} + 0.05711) * e^{(33.91/(T-199.9))}$
R_{sd}	$(0.019447 - 0.008381 * \mathrm{SoC}) + (-3.697e^{-4} + 2.225e^{-4} * \mathrm{SoC}) * dT$
R_{sc}	$(0.0036213 + 0.070237 * \mathrm{SoC} - 0.1539 * \mathrm{SoC}^2 + 0.1064 * \mathrm{SoC}^3) * (0.99971 - 0.012626 * dT)$
R_{ld}	$(0.052543 - 0.032455 * \mathrm{SoC}) - 5.9e^{-4} * (dT) - 2.05e^{-4} * dT * \mathrm{SoC}$
R_{lc}	$(0.092342 - 0.36028 * \mathrm{SoC} + 0.695675 * \mathrm{SoC}^2 - 0.417233 * \mathrm{SoC}^3) * (-2.597e^{-5} * dT^3 + 0.00048845 * dT^2 - 0.012912 * dT + 1.02)$
C_{sd}	$(-669.1413 * \mathrm{SoC}^2 + 1131.16728 * \mathrm{SoC} + 454.727093) + (12.11 - 6.58 * \mathrm{SoC}) * dT$
C_{sc}	$(-5497.15 * \mathrm{SoC}^3 + 7595.2327 * \mathrm{SoC}^2 - 3342.886 * \mathrm{SoC} + 1318.0887) + 8.814 * dT$
C_{ld}	$(-6.711e8 * \mathrm{SoC}^4 + 1.2016e9 * \mathrm{SoC}^3 - 7.0986e^8 * \mathrm{SoC}^2 + 1.64e^8 * \mathrm{SoC} + 1.95e^6) * e^{(-2398/T)}$
C_{lc}	$(-11921.46045 * \mathrm{SoC}^2 + 7634.7588 * \mathrm{SoC} + 5907.7093) * (1.3367e^{-5} * dT^3 + 0.00098996 * dT^2 + 0.040447 * dT + 0.99)$

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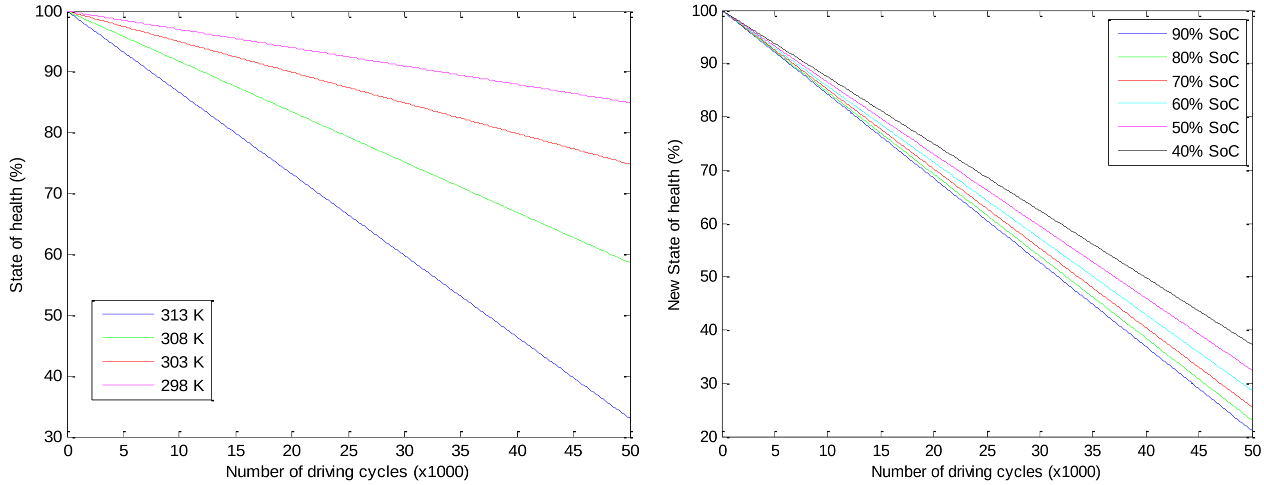

Fig. 4. SoH calculation different initial SoC and temperature.

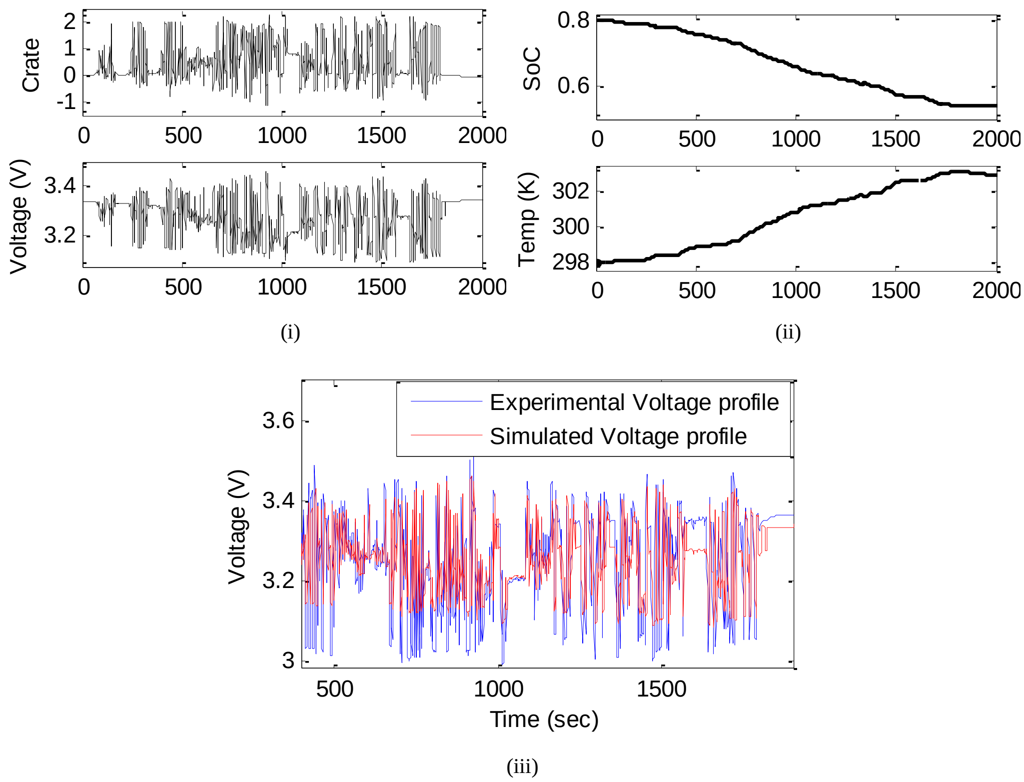

Fig. 5. (i-ii) Current, voltage, SoC and temperature profile. (iii) Real and simulated voltage profiles.

But, in Li-ion chemistry, when the ambient temperature is lower, lithium plating happens in the negative electrode of the battery which degrades the battery in such a way that the available capacity of the battery decreases. So, in lower temperature range, the battery needs to be modeled in a separate way, which has not been investigated in this report.

To validate the previous analytical results, an electric vehicle was subjected to similar operating conditions and the experimentally obtained real vehicle data was used to verify the applicability of the simplified equations and the available capacity degradation analysis. The earlier works [3-5,8] were done with the NEDC profile, which has lower current profile. This paper uses a higher magnitude current profile obtained from real vehicle data and those has been plotted in Fig. 5. It can be seen from Fig. 5 (i-ii) that due to high C-rate of the current profile, SoC decreases from 0.8 to 0.55 in one driving cycle. The interesting fact is that the simulated closed circuit voltage of the system with the real driving profile almost matches with the real closed circuit voltage of the system (Fig. 5(iii)). This essentially validates that the proposed simplified equations and thus the models can accurately predict the behavior of an EV battery system.

TELEN2017004
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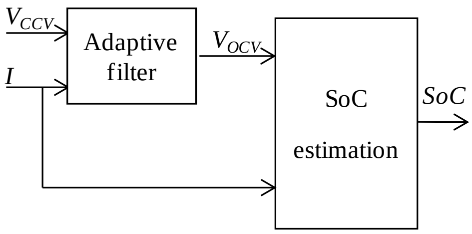

Fig. 6. Online SoC estimation.

III. ONLINE SOC ESTIMATION

Our previous models take the help of the known initial value of SoC to calculate the current SoC. In practical cases, the user may not know the initial value of the state of charge. So, an adaptive SoC estimation algorithm [8,19,20] was developed to adapt the SoC and voltage profile with the actual values. Our main aim is to estimate the state-of-charge of the battery without any prior information of the battery except the measured voltage of the battery and the current profile was subjected to. Fig. 6 describes the model which helps to get the instantaneous value of the open circuit voltage of the battery and the corresponding state-of-charge. The adaptive filter predicts the value of the open circuit voltage/equilibrium voltage of the battery depending on those two input parameters only. To start with, the equivalent circuit of the battery has been approximated with one RC pair. The inputs to the battery model are the current profile and the voltage profile. The mathematical model is described below:

$$\frac{V_z(s)}{I(s)} = \left(\frac{R_s}{1 + sR_s.C_s} + R_o\right) \tag{1}$$

$$G(z) = \left[R_s * \left(\frac{\left(1 - e^{\frac{-T_s}{\tau_s}}\right) * z^{-1}}{1 - e^{\frac{-T_s}{\tau_s}} * z^{-1}}\right)\right] + R_o; \text{where } T_s \text{ is the sampling time, and } \tau_s = R_s.C_s \tag{2}$$

where $V_z(s)$ is the total voltage across the impedances of the equivalent circuit.This can be simplified as

$$G(z) = \frac{b_o * z^{-1}}{1 + a_o * z^{-1}} + b_1 \tag{3}$$

After z transformation of the equation,

$$V_{CCV}(k) = -b_1 * I(k) - b_{oo} * I(k-1) + V_{OCV}(k) - a_o * V_{CCV}(k-1) + a_o * V_{OCV}(k-1) \tag{4}$$

$$V_{CCV}(k) = \Phi_{o(k-1)}{}^{T}.S_{o(k)} \;;\; \Phi_o = [-b_1;\ -b_{oo};\ a_o;\ V_{OCV}(k)] \tag{5}$$

$$S_o = \left[I(k);\ I(k-1);\ \left(V_{OCV}(k-1) - V_{CCV}(k-1)\right); 1\right] \tag{6}$$

The coefficients of the matrix Φ_o were manipulated in successive iterations in such a way that this error gets minimized in the subsequent iterations. So the matrix Φ_o is updated according to

$$\Phi_{o\ k} = \Phi_{o\ k-1} + \Delta\Phi_{o\ k-1} \tag{7}$$

$\Delta\Phi_{o\ k-1}$ is dependent on the minimization of E(k). Using adaptive filter estimation,

$$\Phi_o(k) = \Phi_o(k-1) + C(k) * \left(d(k) - S_o{}^T(k).\Phi_o(k-1)\right) \tag{8}$$

$$\Delta\Phi_{o\ k-1} = C(k) * \left(d(k) - S_o{}^T(k).\Phi_o(k-1)\right) \tag{9}$$

Now, after minimizing the error, the matrix Φ_o will give us the value of OCV, which will be used to estimate the SoC of the battery from the OCV vs SoC curve of the battery. It can be seen from Fig. 7 that, the estimated SoC follows the SoC profile if someone knows the initial SoC. It starts from initial SoC 0.8 and then discharges till SoC 0.7 and then charges till 0.8 again. The adaptive filter estimation also gives the same result.

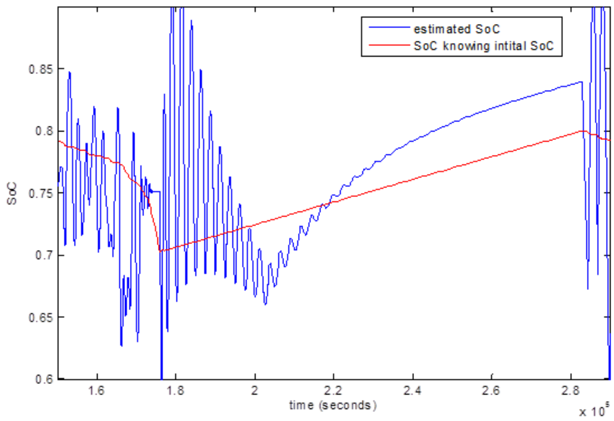

Fig. 7. Comparison of SoC with the knowledge of initial SoC and estimated SoC.

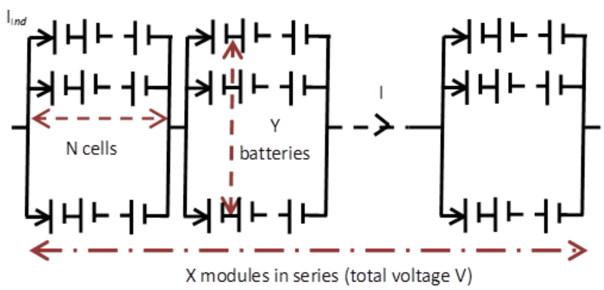

Fig. 8. A simple configuration of a battery pack.

TELEN2017004
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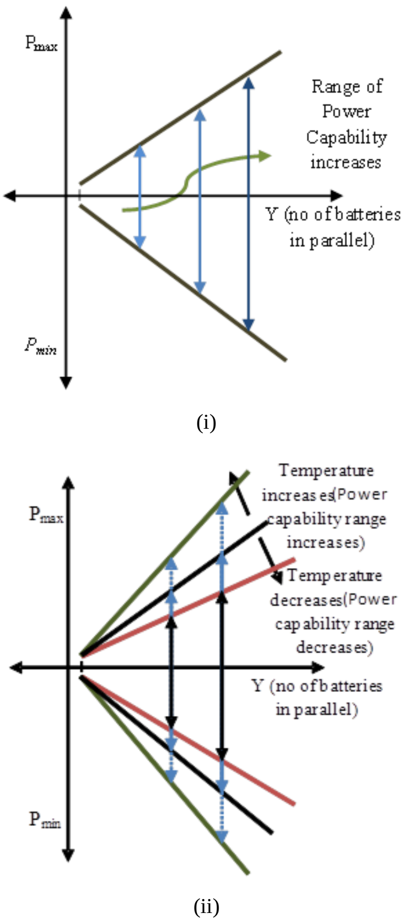

Fig. 9. Power range capability for different number of batteries in parallel and for changing temperature.

IV. Battery Pack Modeling

In most of the practical cases, the electric vehicle (EV) system will have more than one battery to meet the need of the system [21-24]. The batteries will be packed as a battery pack which may have different configurations [22]. Let us assume that there are X number of modules connected in series (Fig. 8). Each module consists of Y number of batteries in parallel and each battery has N number of cells in series. Number of modules (X) and number of cells in series within a battery (N) define the voltage of the battery. Number of batteries in one module (Y) defines its current capability (Ah).

So,

$$V = (V_{ind} * N) * X \tag{10}$$

$$V_{ind} = (V_{OCV} - I_{ind} * Z_{battery}) \tag{11}$$

$$Y = {}^{I}/_{I_{ind}} \tag{12}$$

The total voltage of the battery (V) is

$$V = \left(V_{OCV} - \frac{1}{Y} * Z_{battery}\right) * N * X \tag{13}$$

Now, if the battery is subjected to a power P, then the current to be fed or taken out from a single battery is dependent on the battery voltage V_{ind} at that moment and can be calculated as

$$I_{ind} = \frac{P}{Y * N * X * V_{ind}} \tag{14}$$

Now, the total expected power dissipation P_{diss} is

$$P_{diss} = K * \left[I_{ind}{}^{2} * N * Y\right] * X \tag{15}$$

where K is dependent on the impedances of the battery and is assumed to be same for each battery.

A. State of Power (SoP)

When a battery is used in EV applications, the battery is subjected to different conditions and it must be operated within a safe operating area. Some of the important things to remember while operating a battery are the following:

The battery will be subjected to sudden high power (to be fed or to be taken out). The battery voltage should not go beyond the safe voltage range of the battery.

$$V_{min} \leq V_{OCV} - Z_{battery} * \frac{P}{Y * N * X * V_{ind}} \tag{16}$$

$$V_{max} \geq V_{OCV} - Z_{battery} * \frac{P}{Y * N * X * V_{ind}} \tag{17}$$

$$V_{max} \geq V_{OCV} - Z_{battery} * \frac{P}{Y * N * X * V_{ind}} \tag{18}$$

$$\left(\frac{V_{max} - V_{OCV}}{Z_{battery}}\right) * Y * N * X * V_{ind} \leq P \leq \left(\frac{V_{OCV} - V_{min}}{Z_{battery}}\right) * Y * N * X * V_{ind} \tag{19}$$

For a predefined configuration and pre-determined values of V_{max} and V_{min}, the extreme conditions of power that can be supplied (P) is dependent on the battery pack voltage, the battery open-circuit voltage (V_{OCV}), the impedance of the battery at that moment and the configuration of the battery pack i.e. the values of N, Y and Z.

The system voltage of the battery pack is always determined according to the maximum speed of the vehicle. So, for a pre-assumed maximum speed of the vehicle, the system voltage V is constant. Now, the EV manufacturer needs to decide the type of battery he is going to use. Depending on the chemistry of the battery, the V_{ind} is almost fixed or generally within a certain range (e.g. for LiFePo4 battery, this voltage is within 2.8-3.4 V). So, for certain V, the value Z ∗ N is also constant as

$$N * X = {}^{V}/_{V_{ind}} \tag{20}$$

The values of N and X depend on several factors. With higher number of cells in series (N) within a battery, the size increases and the thermal pattern of the battery and the module changes. So, these values must be carefully chosen to optimize various conditions. In this research, we won't delve into much detail about that. Let us define maximum and minimum power that the battery can supply as P_{max} and P_{min} where

TELEN2017004
DOI 10.14311/TEE.2017.3.062

$$P_{min} = \left(\frac{V_{max} - V_{OCV}}{impedance}\right) * Y * V \quad (21)$$

$$P_{max} = \left(\frac{V_{OCV} - V_{min}}{impedance}\right) * Y * V \quad (22)$$

$$P_{min} \leq P \leq P_{max} \quad (23)$$

So, we can see that maximum power one single battery (so, the battery pack) can supply depend on the number of batteries in parallel (Y) and the impedance of the battery. As we increase the number of batteries in a single module, the current passing through each battery reduces which effectively reduces the voltage stress of the battery. Effectively, this increases the total power capability of the battery pack (Fig. 9). But, the downside of increasing the number of batteries in one module is that the battery management system (BMS) needs to equalize more batteries in terms of the voltage of each battery.

When the battery is subjected to power stress, the initial voltage drop within the battery is caused by the ohmic resistance of the battery, which is the most dominant part of the battery impedance. As, most of the time, the battery will be subjected to highly dynamic power profile (e.g. city driving with numerous starts, stops, acceleration and regenerative braking), due to presence of time constants, the charge transfer resistance and diffusion resistance will not have much effect on the current profile. They will only delay the current response due to the presence of the time constants associated with them.

When an EV is running on a highway, which means the power profile is constant for a longer duration, the effects of time constants die down after some minutes. So, the impedance offered by the battery will increase. This eventually means that the voltage dip will be higher. So, for dynamic profile of power, we will consider only the ohmic resistance of the battery. As already discussed, this resistance does not change appreciably with changing SoC. But, the resistance changes appreciably with temperature. With increasing temperature the resistance decreases and vice-versa. So, from Eqs. we can see that when temperature increases, as impedance decreases, power capability range increases and vice-versa. This is depicted in Fig. 9.

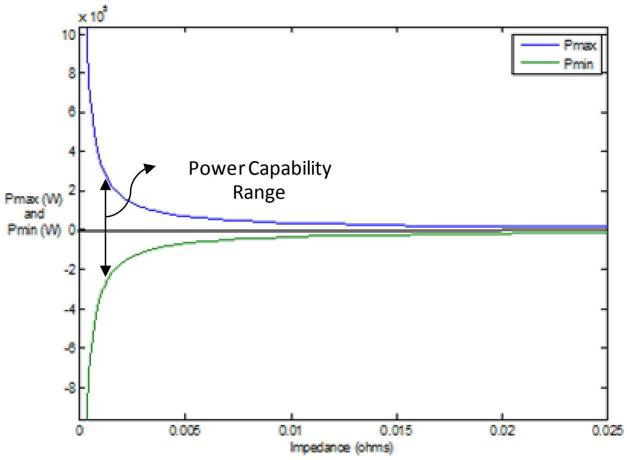

Fig. 10. Power range capability for changing impedance.

The power capability of the battery also depends on the impedance of the battery. As seen from Fig. 10, as the impedance of the battery decreases, the power capability range of the battery increases significantly.

Additionally, the current needed due to the high power requirement should not go beyond the maximum current specified.

$$\left(\frac{P}{Y * V}\right) \leq I_{max} \quad (24)$$

where I_{max} can be assumed as 4 times the nominal current one battery can handle. The value of I_{max} can also be taken from battery specification, if mentioned. Most of the batteries have their capacity mentioned as **S** Ahr with C/H C-rate where H is the number of hours it should take to completely discharge the battery. Then the nominal current of the battery is S/H. From this relation I_{max} can be calculated easily.

B. State of Energy (SoE)

The battery management system should know how much more charge the battery can take or give away. We have already discussed possible effects on the battery in extreme SoC conditions. For longer life of the battery, it should be operated within a range of SoC 0.2–0.8 or even as discussed some literatures, the SoC operating range can be even stricter (0.6-0.8). Accordingly, the amount of more energy it can supply or take changes. Taking 0.2–0.8 SoC range as our operating range, the following calculations are being done.

$$Q(Charging) = (0.8 - SoC) * Q_{usable} \quad (25)$$

$$Q(Discharging) = (SoC - 0.2) * Q_{usable} \quad (26)$$

$$time_{charging} = \frac{(0.8 - SoC) * Q_{usable}}{P/Y * V} \quad (27)$$

$$time_{discharging} = \frac{(SoC - 0.2) * Q_{usable}}{P/Y * V} \quad (28)$$

At any time, the remaining range of the vehicle can also be calculated using the efficiency of the driving cycle. The value of this efficiency (η) is given in Wh/mile or Wh/km. Therefore Range (R) (in km or miles) can be calculated as

$$R = \frac{(SoC - 0.2) * Q_{usable} * Y * V}{\eta} \quad (29)$$

Fig. 11 shows the time required for charging and discharging under different operating regimes which will be set by the vehicle/battery owners according to their own battery usage profiles.

V. SIMULATION RESULTS

Simulink was used to simulate the battery pack with SoP and SoE characteristics. It uses the basic blocks from [4] and uses the equations (16-24) to calculate the state of power of the battery pack. If the power is within the safe operating area of the battery as discussed earlier, that

TELEN2017004
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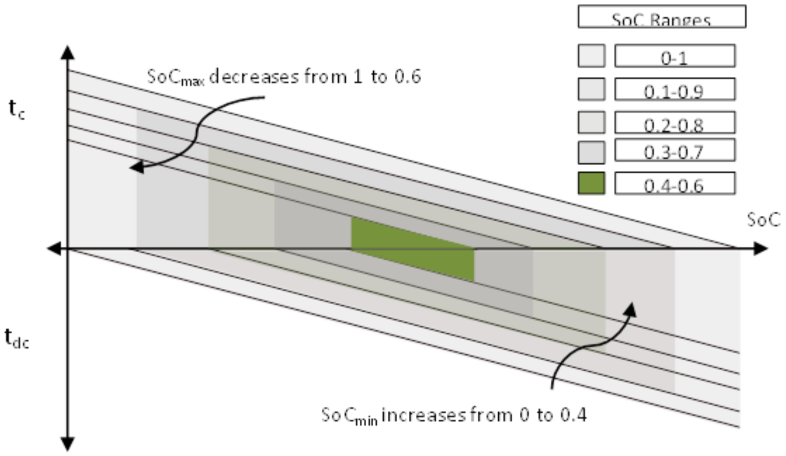
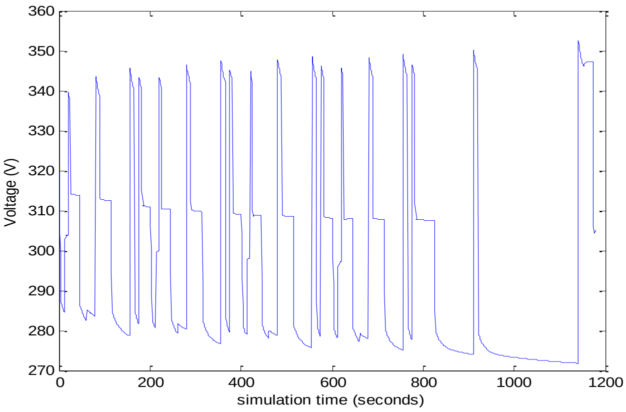
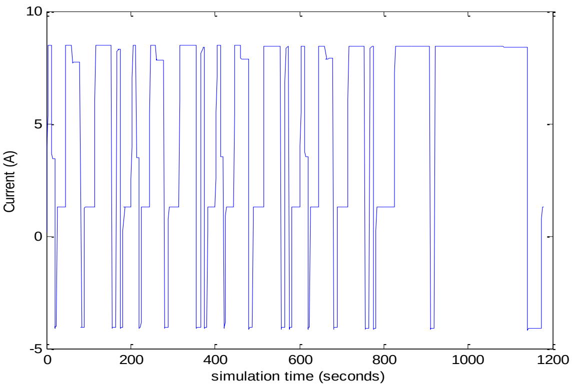


Fig. 11. Time required for charging and discharging under different SoC operating regime.

power is fed to the battery pack. Otherwise, the maximum power that the battery pack can take, that is only send to the battery pack. Eqs. (25-28) are used to calculate the charging-discharging time of the battery and the remaining range of the battery. It also, dynamically calculates the maximum and minimum power that the battery can take into at the next charging-discharging cycle. These values are fed into the SoP check block to calculate the maximum power to be fed to the battery pack. It is worthwhile to mention that we assumed balanced voltage and capacity of all the batteries in the battery pack.



(i)



(ii)

Fig. 12. (i) Voltage and (ii) current profile of the battery.

The input of the model is taken as the power corresponding to the NEDC driving cycle.

With every simulation time, it gives the remaining charging-discharging time and the remaining range of the vehicle. The system was modelled with representative data from the Nissan-Leaf EV, which has system, voltage around 360 V (Fig. 12(i)) and uses the cells which have the capacity 33 Ah at c/10 discharge rate (Fig. 12(ii)).

To prove its self-adjusting power capability, two different simulations have been done with different battery pack configurations. One would have 2 batteries in parallel within a module and another one would have 12 batteries instead of 2. The simulation result is shown in Fig. 13. The simulation results explicitly show the change in the power range capability due to change in number of batteries in parallel. It can be seen that in Fig. 13, the power which can be processed has a range of 2000 W to −2000 W whereas when the system is used with a number of batteries in parallel, it can process more power in a range of 5000 W to −5000 W. As the number of batteries in parallel increases, each battery processes lesser current which eventually helps their voltage to stay within the specified range. It can be seen that when only 2 batteries are in parallel, the power that can be reduced or absorbed is less than when there are 12 batteries in parallel. The simulation result also shows the current profile of the battery pack when used with different configurations. It shows that, although the system actually needs more power, if we have a strict regime of voltage fluctuations of the battery, the power that can be processed by the battery pack will be reduced.

VI. Conclusion

This paper investigates the operation of an electric vehicle battery pack modelling two parts of it: (i) The lithium-ion batteries/cells of each battery pack, (ii) The battery pack considering the different series/parallel configurations.

The cell simplified equivalent circuit model of a lithium ion battery in accordance to practical driving conditions (i.e. referring to Fig. 5 – a real driving profile which is different than well-established test driving profiles such as NEDC) has been analysed and compared against experimentally obtained battery parameters. It was assumed that the battery of an electric vehicle will only be used in the SoC range of 0.2–0.8 (in some cases 0.3–0.7).

TELEN2017004
DOI 10.14311/TEE.2017.3.062

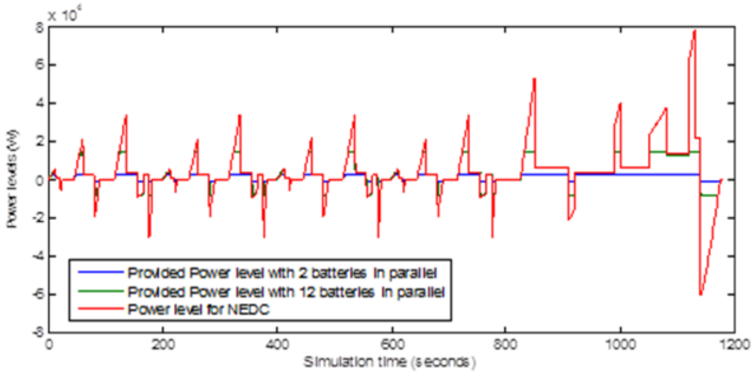


Fig. 13. Different power profiles associated with change in number of batteries in parallel.

Thus the battery circuit parameters can be easily simplified within that working range. The output voltage of the battery using its equivalent circuit model has been compared and validated against an experimentally obtained real battery voltage. Subsequently, the equivalent parameters were used to calculate the performance of the battery when used in a NEDC driving cycle.

Analysis about obtaining the information of the state of charge of the battery without any prior information about the initial state of charge of the battery was also done. It was done only with information of the voltage and current profile the battery was subjected to. The adaptive filter estimation method was used to calculate the open circuit voltage of the battery, so the state of charge of the battery.

The paper also uses the ideas of State of Power (SoP) and State of Energy (SoE) which defines the state of a vehicle battery pack. It states that the battery can only transfer power if its voltage and current are within the safe operating area. It shows that a battery can work well within its safe operating area if the number of batteries in parallel (Y) is greater. With greater number of batteries, each battery is subjected to less current and thus the battery voltage does not reach its minimum and maximum safety limit often. This in turn, increases the usable capacity of the battery and thus increases the range of the vehicle battery.

It also analytically shows the range of the battery under charging and discharging. The effects of temperature, SoC operating regime and impedance of the battery have been shown in this paper.

Further studies can be done to characterize the battery parameters in low temperatures. Lithium plating of the battery needs to be investigated to get a full picture of the battery parameters in all kinds of driving conditions.

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TELEN2017004
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