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Battery model for life-preserving conditions

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Short Abstract

In this paper a battery model for life-preserving conditions is developed. For the identified adverse effects, a battery operation range is defined. The operation range is wide enough to obtain good performance of the battery but it also prevents battery malfunctioning and the need of battery replacement decreases. With a close-up operation range, a new mathematical battery model with both accuracy and fast-processed can be determined.

Keywords: battery model, BEV, simulation, range, modeling

1 Introduction

A battery electric vehicle (BEV) uses electrical energy stored in a battery to supply power to the electric motor and to guaranty the operation. New energy management techniques have been developed to improve the electric range of the vehicle, but to be effective, the estimations about battery variables (voltage, current, SOC, SOH…) must be accurate and fast-processed. The estimation of an accurate electric range is also an important matter due to the consumer fear of running out of electricity while driving, often referred as “range anxiety” [1].

The most critical variable is the battery voltage. The cell voltage of a battery has a narrow window of operation and the change in the voltage cell is closely related to the battery life. If the voltage falls below the 2.5V the cell loses its capability of storing energy and if the voltage increases above 4.25V the pressure inside the cell will increase. A precise estimation is necessary to guarantee the health of the battery [2].

The prediction of battery voltage is complex due to the change in the battery behaviour at high currents and low state of charge. In order to make estimations in these adverse circumstances, battery models are often computationally time-consuming. The overall runtime is, therefore, compromised even when this operation conditions in real life are rare.

These situations cause the mayor changes in the cell voltage, and must be avoided. Guarantee the operation of the battery between certain limits increases the battery life. Also, it provides a framework that allows less complex models predict battery variables with accuracy.

2 Problem Statement

The development of high-speed accurate battery model requires the definition of an operation framework. This framework is established from the adverse effects in the battery technology chosen. The battery model presented in this paper is developed to obtain a long battery life without compromising the performance of the vehicle.

A mathematical approach is chosen and implemented in MATLAB/SIMULINK. It offers a high-speed prediction and good accuracy but these models only work in particular applications. In this paper, a detailed analysis of the V-I characteristics of the chosen battery is developed. This analysis is only valid for this particular battery, but it offers a guide for future works to implement this mathematical model.

3 Battery selection

A LiFePO4 Li-ion battery is chosen for this study. Between the different alternatives, Li-ion technology offers the highest electrochemical density. It provides 2 to 3 times more power density than Ni-Cd o Ni-Mh batteries. Although, Li-ion batteries have also some disadvantages: low thermal stability, toxicity and high cost of its main cathode material (LiCoO2) [3].

Recently some of these disadvantages have disappeared due to the use of new cathode materials, like lithium iron phosphate. LiFePO4 batteries are cheaper and have higher durability and thermal stability. Due to the absence of cobalt, LiFePO4 batteries are also less toxic. However, the iron phosphate has less conductivity and these batteries can provide lower rates of current. There are currently open investigations that are testing new synthesis process to solve this problem [4].

The battery chosen in this paper is the GP45EVLF modules, commercialized by EVB Technology. These battery modules are specifically developed to use in electric vehicles and the detailed datasheet can be consulted in [5].

160 in series modules are used to obtain a rated voltage of 512 V. The energy capacity of this assembly is 23.04 kWh, and a weight of 224 kg. These characteristics correspond to academic design examples [3 [6], and also to commercial electric vehicles [7] [8].

3.1 Adverse effects of Li-ion batteries

Li-ion batteries do not suffer from memory effect or the superficial charge effect that occurs in Pb-batteries, but they have other operation limitations such as the described below [2]:

- Maximum discharge current

The current that can be provided is related to the power of the battery. The current demanded has a huge impact in the performance of the battery and high current rates are avoided if possible. In case of electric vehicles, the battery must be sized with the maximum power of the electric motor; therefore, the maximum current is not exceeded in any point of operation. If the battery is not sized accordingly, a protection circuit must be considered but the performance of the vehicle is compromised.

- Overcharge effect

Once the 90% of the capacity of the battery is reached, the charge current applied does not transform the chemical actives but produce adverse effects like the corrosion of the electrodes, electrolytic decomposition, etc. In addition a process of runaway occurs. The charge current increases, which make the temperature rise. The temperature causes the increase of the conductivity of the internal resistance, therefore the charge current increases.

- Self-discharge effect

If the battery is in open circuit (namely, storage or un-used), the battery gradually loses its charge due to the temperature and the impurities in cell elements. Therefore, the moment the vehicle is not running, a fraction of the store energy is lost. The rate of self-discharge depends on the charge conditions and the battery temperature.

- State Of Health (SOH)

The cell capability to store energy is reduced with the time and use. The state of health measures the remaining capacity of a battery with regard to the nominal capacity. It is related with the number of discharge cycles. A discharge cycle is completed when the discharge capacity (in Ah) is the battery capacity at 1C rate.

It is important to emphasize that these effects can be avoidable by using the battery inside certain operation limits. However, the limitation causes that the nominal capacity of the battery cannot be used. With tighter restrictions, the battery life would be improved, but the battery should be oversized to guaranty the performance of the vehicle. It is necessary to determine these limits adequately to make the most of this trade-off [3].

The model developed in this paper takes into account these effects and provides efficient limits to impose to the battery operation from the battery characteristics.

3.2 Limit definition

The limits in the battery operation are determined by the adverse effects described. To prevent the battery from supplying current adobe the maximum discharge current, a protection circuit will be considered. This solution can be used to control, not only the discharge current, but the charge current also. The maximum discharge and charge currents are provided in the battery datasheet.

The overcharge effect can be avoidable by applying an upper limit to the state of charge of the battery. According to previous documentation [9] [10], this limit can be located in the 90% of SOC. In the design example proposed in [6], the electric energy has multiple origins: the electrical grid, the thermal engine or the regenerative braking. To charge the battery from the electrical grid, protection systems must be considered to guarantee that the upper limit is not exceeded.

The thermal engine is managed to disconnect itself when the 80% of the SOC is reached, to give a margin to the regenerative braking charge. The regenerative braking charge can be regulated by the use of the conventional brake system. When the SOC reaches the upper limit, the hydraulic break system takes over the braking needs, avoiding the overcharge of the battery. The SOC of the battery can be calculated dynamically using Peukert’s Law as shown in [11]. As this issue has already been resolved with an acceptable precision and calculation delay, it is not described in this paper.

Besides SOC calculation, a battery model has two objectives: calculate the battery wear and voltage. The study of the battery wear requires different tests that are not usually provided by the manufacturers. In that case, the manufacturers provide an estimation of battery life and guarantee a certain capacity for a number of cycles.

Battery datasheet [5] guarantees the 80% of the capacity at 1C (45 A) after 1500 cycles. This statement is used in the battery model as a limit of performance: from 1500 cycles the battery is not usable. The remaining capacity is low and the overcharge effect needs to be dynamically manageable, the control more complex. The delay in calculations and the battery range drop justify the replacement of the battery.

It is also necessary to determine a lower limit to the SOC of the battery to avoid a drastic change in the battery voltage. This limit can be obtained from a detailed study of the discharge curves.

4 Model definition and implementation

The model is divided in two parts, according to the following functions:

4.1 Battery voltage determination

The change in battery voltage causes the change in the discharge current at equal power demand, altering the operation conditions. The battery model should be capable of relation these two variables dynamically and in short runtime to be implemented in the electronic controller.

The battery voltage depends on the stage of charge, the discharge current and the battery itself. The discharge curves are shown in Figure 1 and Figure 2.

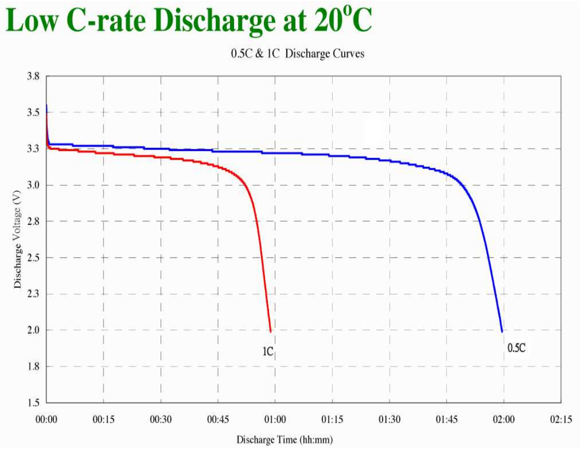

Figure 1. Discharge curves – Low discharge[5]

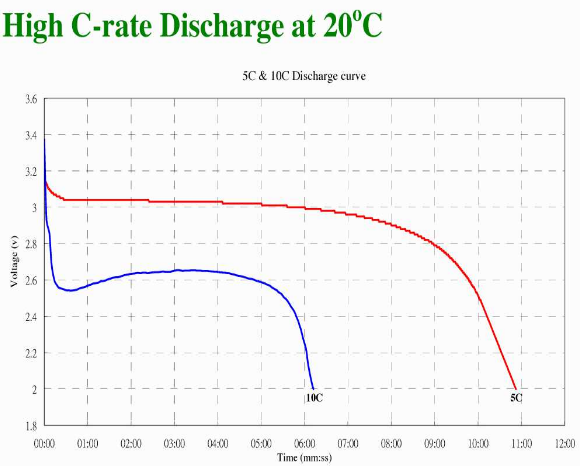

Figure 2. Discharge curves – High C-rate discharge[5]

Figure 1 and Figure 2 show not only the discharge time but the battery voltage (VDC) for each current. With the data provided by these curves, a mathematical relationship can be established. For a given SOC and discharge current, an estimation of battery current can be obtained.

It is easily observed that the relationship between the battery voltage and the time of discharge is linear except in early and final operation. In early operation the battery chemicals are not stable and there is a danger of overcharge effect in case of regenerative braking.

In final operation, the state of charge is low and the battery cannot provide the same power. States of charge below this limit (30% in the case studied) compromise the performance and health of the battery. The battery voltage decrease rapidly and the current increment associated constitutes a risk.

Operation below or above the linear limit is not considered. For each current, four points have been selected as representative operation data. These points are shown in Table 1.

$I_{discharge}$ = 22,5 A		$I_{discharge}$ = 45 A	
T (min)	VDC	T (min)	VDC
0	3,36	0	3,3
30	3,3	15	3,25
60	3,25	30	3,2
90	3,2	45	3,15
T total discharge = 117,72		T total discharge = 58,56	
$I_{discharge}$ = 225 A		$I_{discharge}$ = 450 A	
T (min)	VDC	T (min)	VDC
0	3,05	0	2,7
6	2,97	2	2,675
7	2,95	4	2,65
8	2,9	5	2,6
T total discharge = 11,57		T total discharge = 5,76	

Table 1. Battery voltage at different discharge current rates.

According to Table 1, there are two variables to consider: the discharge current and the discharge time. The discharge current provides the instantaneous operation. The discharge time is related to SOC. The state of charge provides a measure of the remaining capacity that does not depend on the current; therefore it is a more suitable variable to study.

To establish a relationship between battery voltage and both variables (discharge current, SOC) it is necessary to study the relationship with each of the variables separately.

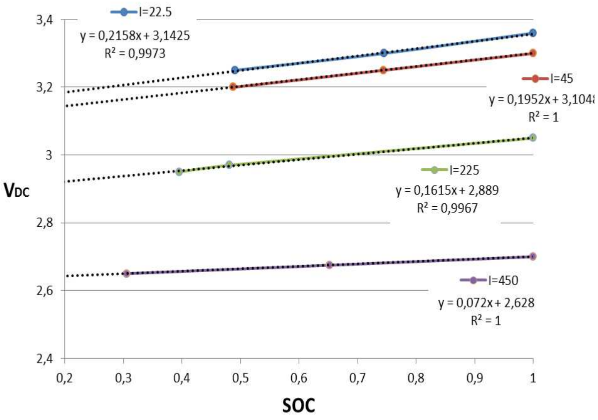

Figure 3. Battery voltage – SOC linear tendency curves

Figure 3 shows the relationship between battery voltage and SOC. Within the operation range considered (90% to 30% SOC) the relation is clearly linear. The tendency curves provide an accurate estimation of the operation points. Even the weakest linear estimation provides a good precision (for a discharge current of 225 A, R2=0.9967).

Outside this operation range a linear estimation is not enough to predict the value of V_{DC}, but this behaviour is not allowed to prevent adverse effects. Including the points of operation outside the range is computationally time-demanding, and does not provide an actual improvement if this condition is not ever met.

Once determined the relationship between battery voltage and SOC, it is necessary analysing the dependence on the discharge current. With the expressions obtained in Figure 3, the value of V_{DC} for four values of SOC within the operation limit (0.3, 0.5, 0.75, 0.9) can be obtained. Representing these new operational points, as shown in Figure 4, the relationship between battery voltage and discharge current is easily observed.

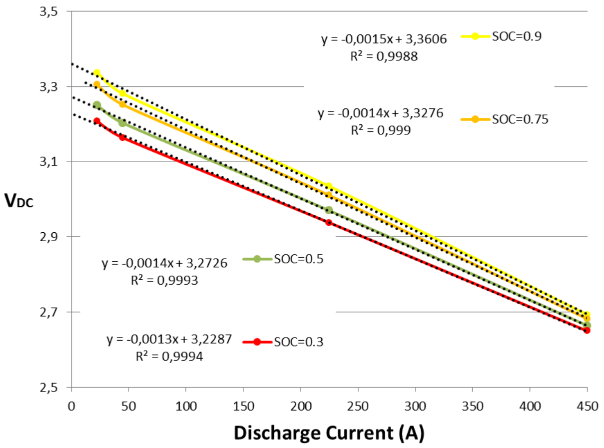

Figure 4. Battery voltage – discharge current linear tendency curves

It can be inferred from Figure 4 that the relation between battery voltage and discharge current (within the SOC range allowed) is linear. This estimation provides good precision, with a minimum R2 = 0.9988. This can be seen as a Thevenin equivalent circuit, where the Y-intercept is the open-circuit battery voltage (OCV) and the gradient represent the battery series resistance for each value of SOC. This circuit model is represented in Figure 5.

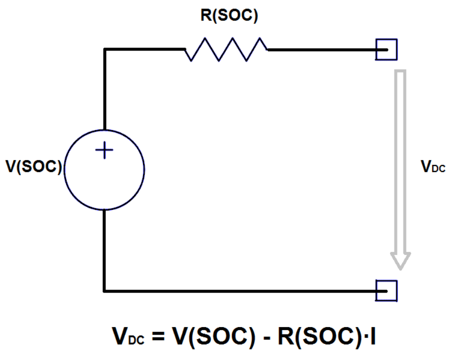

Figure 5. Battery Thevenin equivalent.

This correspondent circuit model provides a validation comparing to the datasheet. Even though the value of OCV varies in a wide range, the internal resistance varies in less than 0.2 mΩ. According to Figure 4, the total internal resistance of the battery is below 2 mΩ, as indicated in the datasheet.

To sum up, the battery voltage depends linearly on the discharge current and SOC, therefore it is possible to establish a bilinear interpolation. Results are shown in Table 2 and Table 3.

Interpolation statistics	
Multiple correlation coefficient	0.9980
Correlation coefficient R2	0.9960
Adjusted R2	0.9951
Typical error	0.0184
Observations	12

Table 2. Interpolation statistics

	Interception	SOC	I discharge
Coefficients	3,22E+00	1,47E-01	-1,41E-03
Typical error	1,77E-02	2,15E-02	3,14E-05
Statistic t	1,82E+02	6,82E+00	-4,51E+01
Probability	2,36E-17	7,71E-05	6,51E-12
Lower 95%	3,18E+00	9,82E-02	-1,49E-03
Upper 95%	3,26E+00	1,96E-01	-1,34E-03
Lower 95,0%	3,18E+00	9,82E-02	-1,49E-03
Upper 95,0%	3,26E+00	1,96E-01	-1,34E-03

Table 3. Correlation coefficients and deviation

The estimation is resolved with a correlation coefficient R2 = 0.996 for the operation conditions previously described. In the case studied, the battery voltage varies from 3.4 to 2.6 Volts and can be calculated from Equation (1).

$$V_{DC} = -0.001414 \cdot I_{dc} + 0.146914 \cdot \mathrm{SOC} + 3.215554 \qquad (1)$$

Since the precision of the tendency curve calculated is acceptable, Equation (1) will be implemented in the battery model. However it is necessary to keep in mind that the real error is determined from the validity of the discharge curves. For the implementation in an electric vehicle, battery discharge test need to be carried out and more points of operation need to be considered.

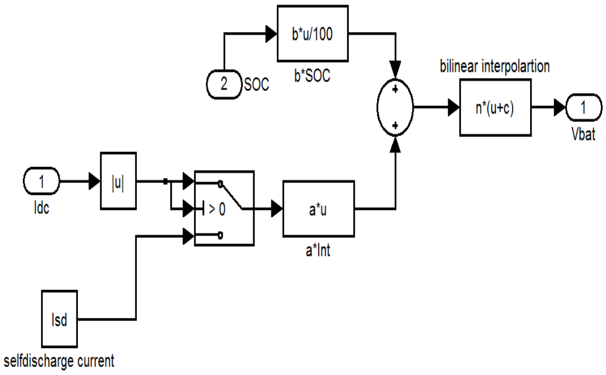

Figure 6. Implementation of battery voltage calculation in MATLAB/SIMULINK

Figure 6 shows implementation of Equation (1) in MATLAB/SIMULINK. This model is annexed in the vehicle model described in [5].

4.2 Number of cycles determination

To calculate the number of cycles, first the capacity at 1C must be determined. According to the datasheet, the result is shown in Equation (2).

$$\mathrm{C}_{1C} = 45 \cdot 0.967 = 43.52\ \mathrm{Ah} \qquad (\ 1)$$

Relating this capacity to the discharge current, the number of cycles (N) is calculated as shown in Equation (3).

$$N = \frac{\int i(t)dt}{3600 \cdot \mathrm{C}_{1C}} \ \text{ para } i(t) > 0 \qquad (\ 2)$$

The simulation stops if N reaches 1500.

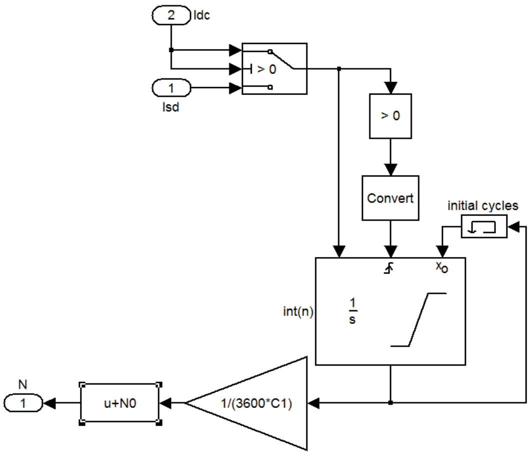

Figure 7. Implementation of number of cycle's calculation in MATLAB/SIMULINK

Figure 7 shows the implementation of Equation (3) in MATLAB/SIMULINK. This model is annexed in the vehicle model described in [5].

5 Simulation results

NEDC speed profile is used as input data for the vehicle and battery model [11].The NEDC cycle combines four urban cycles, with a low power demand, followed by one extra-urban cycle, that models highway conditions and high power demand [12]. Three operational scenarios are considered, and battery voltage and SOC is analysed.

The first scenario represents vehicle operation in the NEDC cycle. Figure 8 shows the variation in the SOC of the battery. As it could be predicted, the SOC varies largely in the extra-urban part of the cycle, reaching a value of 74.5%.

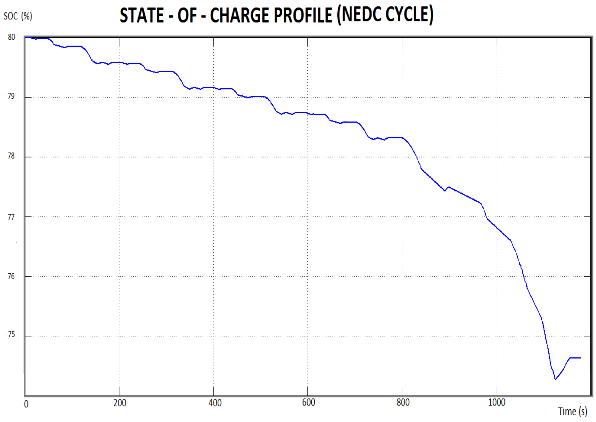

Figure 8. Battery SOC (%) versus Time (s) – 1st scenario

Figure 9 shows the variation of battery voltage for the NEDC combined cycle. The voltage varies in less than 20V, with slightest variations in the urban part of the cycle and greatest variations in the extra-urban one. This is caused because of the high power demand, which concludes in a high discharge current.

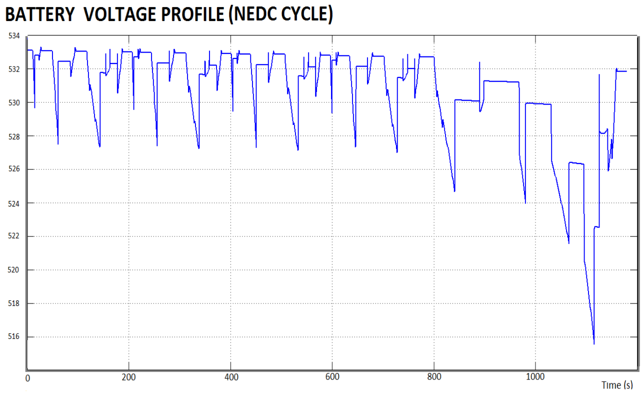

Figure 9. Battery voltage (v) versus Time (s) – 1st scenario

The second scenario represents vehicle operation in pure electric mode. From a SOC 80%, the battery is drained in normal operation modelled by repetition of the NEDC cycle. The simulation stops when it reaches the lower limit SOC 30%.

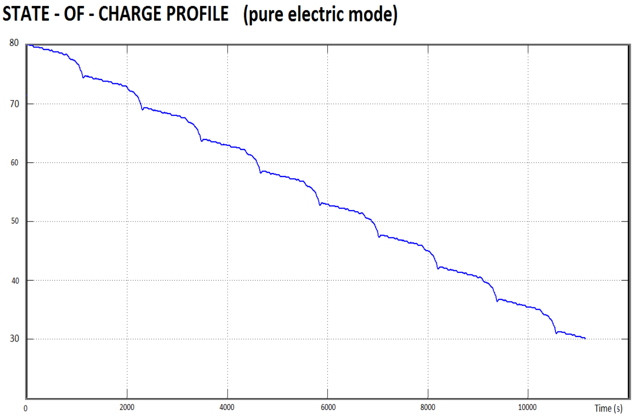

Figure 10. Battery SOC (%) versus Time (s) – 2nd scenario

Figure 11 shows the variation of voltage for the multiple repetitions of NEDC cycle, analysing the entire range of possible values of SOC. From the 80% to the 30%, battery voltage varies in a fewer margin with the decrease of SOC. However, it is clear that the tendency is the reduction of the battery voltage when the SOC decreases. It shows the concordance between the model and the behaviour of a real battery.

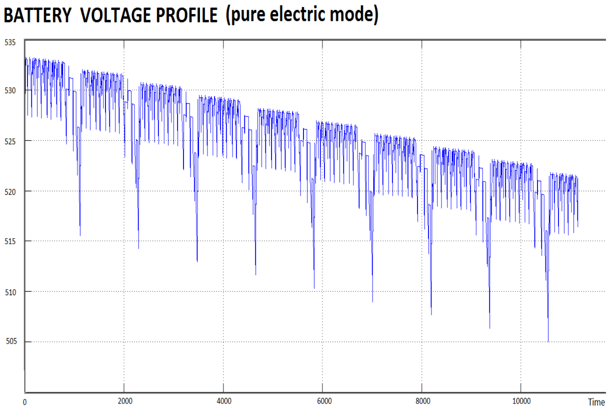

Figure 11. Battery voltage (V) versus Time (s) – 2nd scenario

The third scenario represents an entire discharge cycle. Figure 12 shows the variation in the SOC of the battery for this operation condition. In this case, it can be seen the recharge of the battery due to the thermal engine-generator. When the battery is drained, the SOC reaches its minimum value (30%) and the thermal engine is started. The battery is charged until the SOC upper limit (80%). Both situations take place for a single cycle of charge.

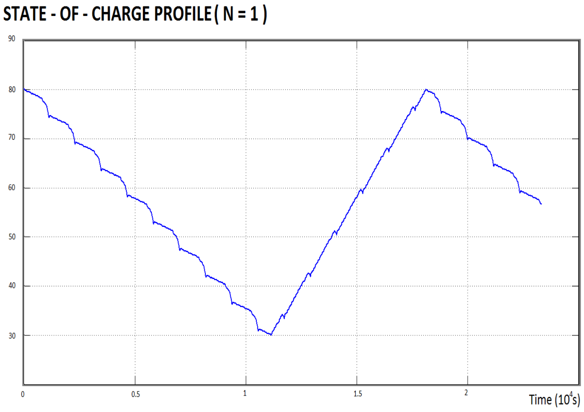

Figure 12. Battery SOC prediction – 3rd scenario

Figure 13 shows the battery voltage profile for the third scenario. As it can also be seen in Figure 11, the battery voltage depends on SOC. Nevertheless, in the charge period the battery behaviour is smoother. High peaks are not reached because motor current demand can be supplied mostly by the thermal engine. The current drained from the battery in this situation is smaller, therefore, the battery voltage changes only in a small margin.

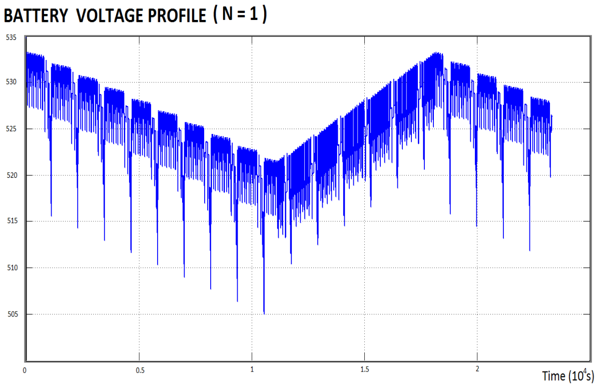

Figure 13. Battery voltage (V) versus Time (Ms) – 3rd scenario

6 Conclusions

The mathematical model presented in this paper is both accurate and fast-processed. It is based in the actual performance of the battery, and the calculation methods used in the example can be applied to any battery in the market. Accuracy can be improved with battery tests in real-life conditions, but the study method stands.

The calculation time is short compared with electric and electro-chemical models. The expression derived can easily be implemented in an ECU: the battery voltage can be calculated solely with the measure of an ammeter. The current demanded from the battery can be used to establish the value of SOC (the integral can be reduced to an infinitesimal sum) using a microcontroller. Any other model could hardly be implemented on-board a vehicle.

Three case scenarios are proposed for the validation of this battery model. One represents the NEDC cycle, and provides an accurate estimation of homologation results. Another represents the behaviour of an electric vehicle, from charged to drained battery. The last one provides a representation of the behaviour of an E-REV.

The simulation provides results that are according to other commercial vehicles and concept cars [14][15] [16]. The implementation of an on-board application provides a step forward massive commercialization of hybrid and electric vehicles.

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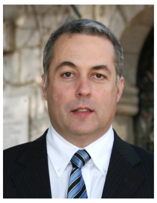

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