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Modelling and Simulation of a Lead Acid Battery for Traction Applications

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ABSTRACT:

In this paper, modeling of a lead acid battery was done by electrical equivalent circuit approach. Model based equivalent circuit approach was used to find the state of charge, terminal voltage, cell temperature and life of the battery at various temperatures. Based on complexity and accuracy, Thevinin's third order equivalent battery model was simulated using MATLAB Simulink software. The simulation results were validated with the experimental state of charge and terminal voltage values.

KEYWORDS:

Cell temperature; Equivalent circuit approach; State of charge; Terminal voltage; Thevinin's third order circuit

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1. Introduction

Now-a-days, hybrid electric vehicles are drawing more attention. They are driven by electric motors, whose supply is given by rechargeable batteries. There are different types of rechargeable batteries. Amongst them, lead acid battery, irrespective of its disadvantages like less energy and power densities, its features like low cost, high starting current, less maintenance, low internal resistance and easier recycling procedure are attractive for present traction applications. It is very difficult to predict its performance accurately. Hence, modeling of such a battery is very important. This paper deals with the dynamic modeling of the battery. There are different battery model techniques like electrochemical model [1], physical model [2] and equivalent circuit model [3]. Equivalent circuit model approach is apt to find out the characteristics of the battery at quick charging and discharging currents, assessing the impact of temperature on the state of charge (SOC), terminal voltage and life. There are different equivalent circuit model approaches like simple battery model, advanced battery model and Thevinin battery model. Amongst them, Thevinin battery model [2] is preferred as its parameters are not constant and predictions are accurate.

In this paper, modeling of a lead acid battery was undertaken by using Thevinin's third order equivalent circuit approach. The battery model was simulated using MATLAB Simulink software to determine the state of charge, terminal voltage, cell temperature and life of the battery at various temperatures. Predicted simulation results were validated with the experimental state of charge and terminal voltage values.

2. Mathematical modelling

The simplified equivalent circuit for Thevinin third order model is shown in Fig. 1. It consists of main branch [3] and parasitic branch [3]. Main branch determines the battery dynamics. Parasitic branch deals with the behaviour of the battery at the end of charge. The open circuit voltage of battery (EMF) is given by,

$$E_m = E_{m0} - K_E(273+\theta)(1-SOC) \quad (1)$$

Where E_{m0} is the open-circuit voltage in volts at full charge, θ is the electrolyte temperature in °C and $K_E = 0.8\times 10^{-3} V/^{\circ}C$. The resistance at the terminals of the battery is given by,

$$R_0 = R_{00}(1+A_0(1-SOC)) \quad (2)$$

Where R_{00} is the value of R_0 at 100% SOC and A_0 is a constant. The resistance at the main branch, R_1, is given by the following exponential relationship,

$$R_1 = -R_{10}\, ln(DOC) \quad (3)$$

Where R_{10} is a constant and DOC is the depth of discharge.

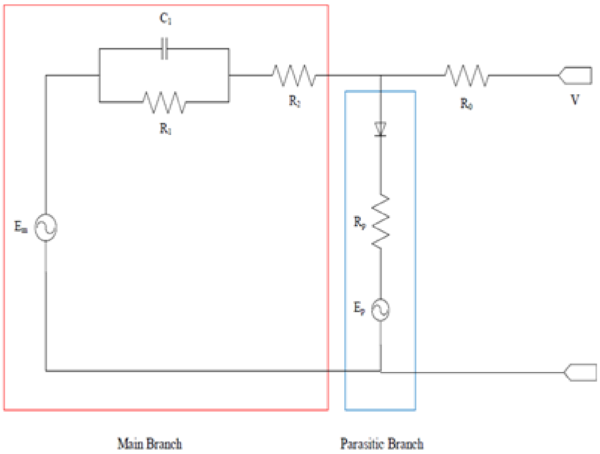

Fig. 1: Thevinin's equivalent circuit model

The resistance at second branch, R_2, is given by,

$$R_2 = \frac{R_{20}\exp(A_{21}(1-SOC))}{1+\exp(A_{22}I_m/I^*)} \quad (4)$$

Where R_{20} is a constant in ohms, A_{21} and A_{22} are constants. I_m is the current in main branch in amps and I^* is the nominal current of the battery in amps. The current at the parasitic branch, I_P, is given by,

$$I_P = V_{PN}G_{po}\exp\left[\frac{V_{PN}V_P}{V_{PN}/\tau_p S+1} + A_P\left(1-\theta/\theta_f\right)\right] \quad (5)$$

Where V_{PN} is the parasitic branch voltage, G_{po} = 2×10^{-12} seconds, τ_p is the time constant of the parasitic branch in seconds, V_P = *12 V*, A_P = 2 and θ_f is the electrolyte freezing temperature in ºC. The charge extracted by the battery, $Q_e(t)$, is given by,

$$Q_e(t) = Q_{eint} + \int_0^{\tau} -I_m(\tau)d\tau \quad (6)$$

Where Q_{eint} is the initial extracted charge in amp sec, τ is the integral time value and T is the simulation time in seconds. The capacity of the battery at a particular temperature and current is given by,

$$C(I,\theta) = \frac{K_C C_0^*\left(1-\theta/\theta_f\right)}{1+\left(k_C-1\right)\left(1/I^*\right)^m} \quad (7)$$

Where K_C = 1.2, C_0^* is the capacity in amp sec at 0°C and no load and *I* is the discharge current in amps and k_C = 1.4. The SOC and DOC are given by,

$$SOC = 1 - Q_e/C(0,\theta) \quad (8)$$

$$DOC = 1 - Q_e/C(I_{avg},\theta) \quad (9)$$

Where Q_e is the charge of the battery, C is the capacity of the battery in amp sec and I_{avg} is the mean discharge current in amps and is given by,

$$I_{avg} = I_m/(\tau_1 S+1) \quad (10)$$

Where τ_1 is the time constant in seconds of the main branch. The electrolyte temperature, $\theta(t)$, is given by,

$$\theta(t) = \theta_{int}\int_0^t \frac{P_S - (\theta-\theta_a)/R\theta}{C\theta}d\tau \quad (11)$$

Where θ_a is the ambient temperature in °C, θ_{int} is the initial battery temperature in °C which is assumed to be equal to ambient temperature, $P_s = i^2R$ is the power loss of R_0 and R_2 in watts, R_θ is the thermal resistance in °C/W, C_θ is the thermal capacitance in J/°C and τ is the integration time variable.

The life of the battery in days is given by,

$$L = L_R D_R C_R/(d_{cycle}+d_{calender}) \quad (12)$$

$$d_{calender} = \frac{calender\ rate}{365} * \tau_R \quad (13)$$

$$d_{cycle} = \left(\frac{D_A}{D_R}\right)^{u_0} e^{u_1}\left(\frac{D_A}{D_R}-1\right)\left(\frac{C_R}{C_A}\right) \quad (14)$$

Where D_R is the rated percentage of DOC, C_R is the capacity at rated discharge current, L_R is the rated life of the battery in cycles, τ_R is the battery charge life, $Ah = L_R D_R C_R$, Calendar rate is the self discharge of the battery, C_A is the capacity at given current, D_A = 1-*SOC* is the depth of discharge and μ_0 & μ_1 are the coefficients. Almost all the parameters of the battery model are constant except C_0*, R_{00} R_{10} and A_0 [4]. C_0 is obtained by the following equation [5]:

$$C_0^* = C_n/\left(1+(I/I^*)^m\right) \quad (15)$$

Where C_n is the rated capacity of the battery, R_{00}, R_{10}, and A_0 are the experimental resistance values obtained from the experiments at the start and end of the test.

3. Results and discussions

A MATLAB Simulink model was developed using the equations presented in the previous section and is shown in Fig. 2. The inputs given to the simulation model such as SOC, terminal voltage, cell temperature are shown in Figs. 3, 4, 5 and 6 respectively. The final values are given in Table 1. Constant current of 2.2 A was given as input. As shown in Fig. 7, the corresponding SOC and terminal voltage were validated with experimental data as shown in Figs. 8 and 9 respectively. Obtained SOC from simulation was 23.3% where as from the experiments, the SOC was 23.4%. The obtained terminal voltage from the simulation was 12V and matched the experimental voltage of 11.9 V. Drive cycle as shown in Fig. 10 was given as the input for the Simulink model. As shown in Fig. 11, the obtained SOC of 0.6219 from the simulation was validated with that obtained from GT suite as 0.6217.

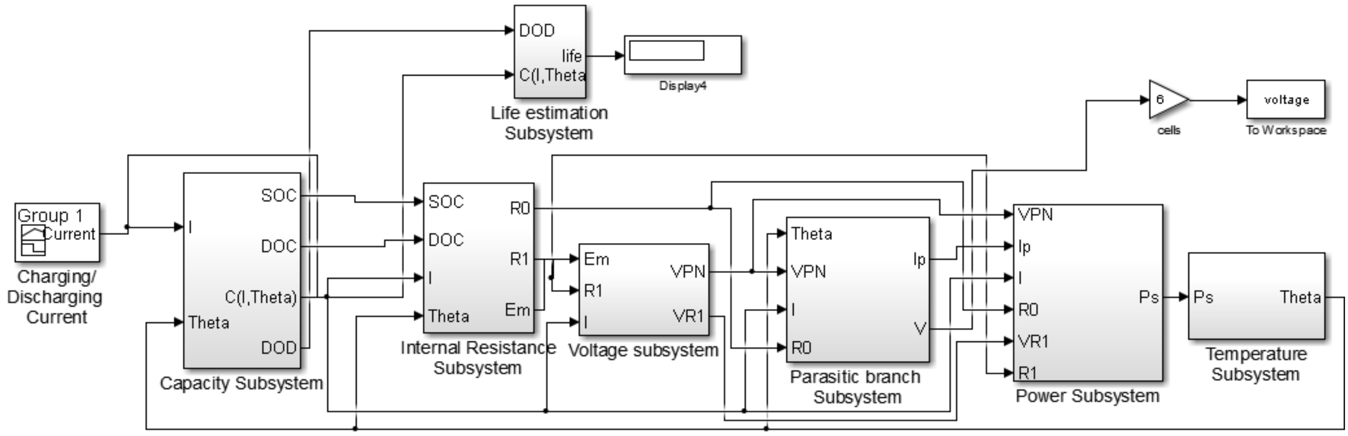

Fig. 2: MATLAB Simulink model of a lead acid battery

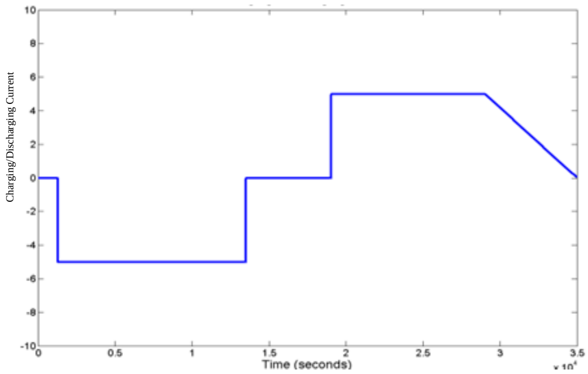

Fig. 3: Input current

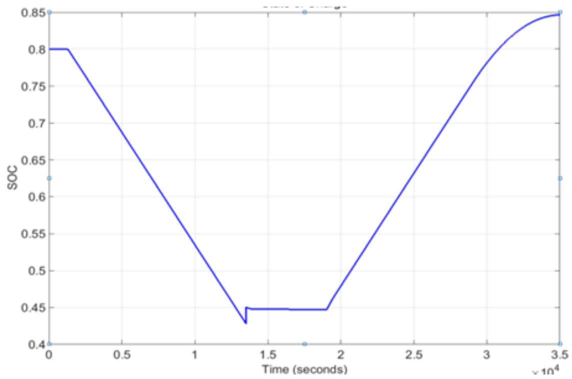

Fig. 4: Input SOC

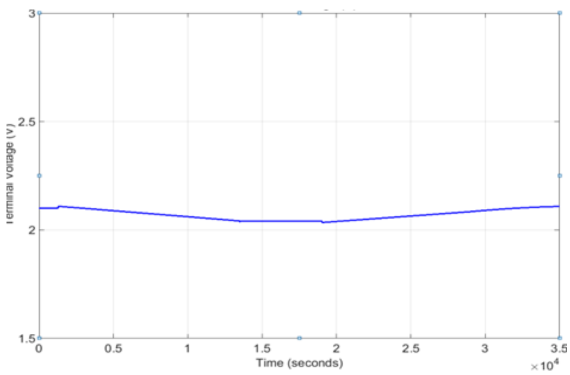

Fig. 5: Input terminal voltage

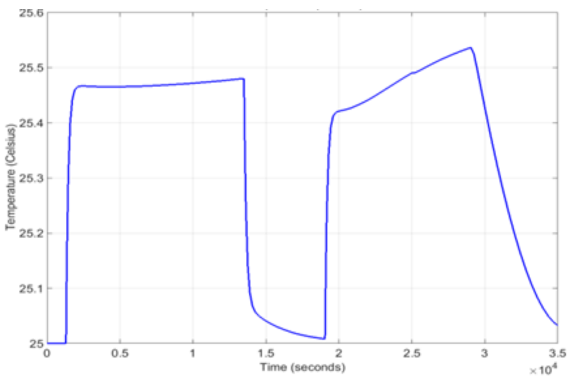

Fig. 6: Input Cell temperature

Table 1: Final values

Parameter	Values
SOC	0.84
Terminal voltage	2.15 V
Cell temperature	25.03 °C
Life	5.7 years

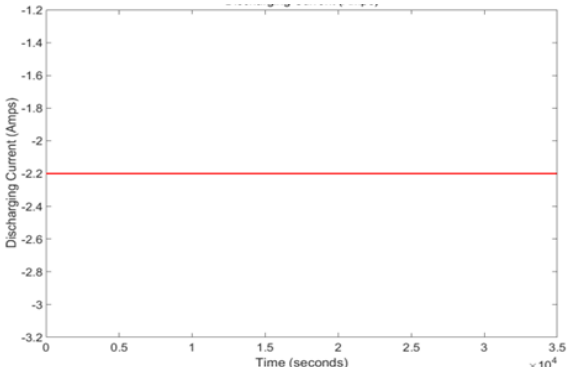

Fig. 7: Discharging current

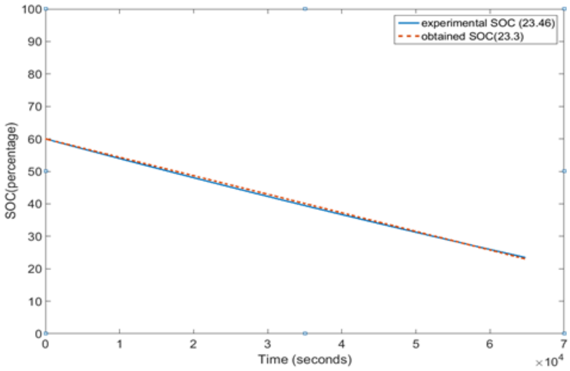

Fig. 8: Validation of SOC output

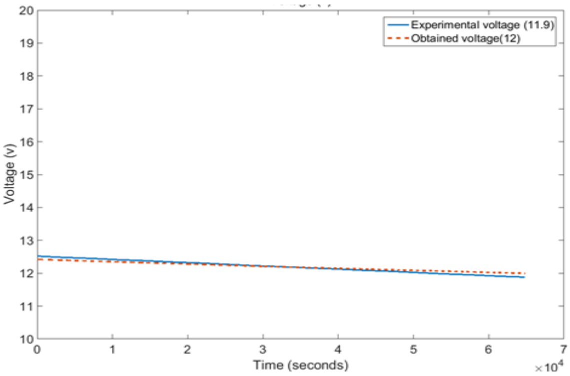

Fig. 9: Validation of terminal voltage output

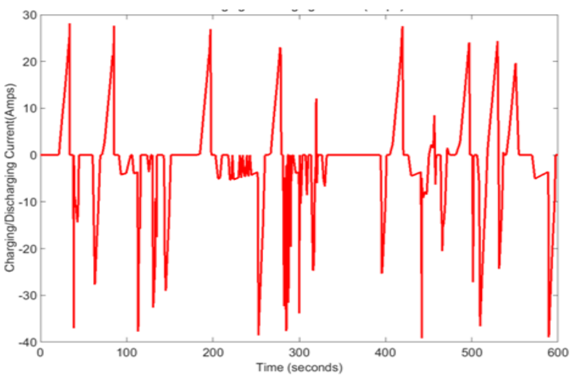

Fig. 10: Drive cycle given

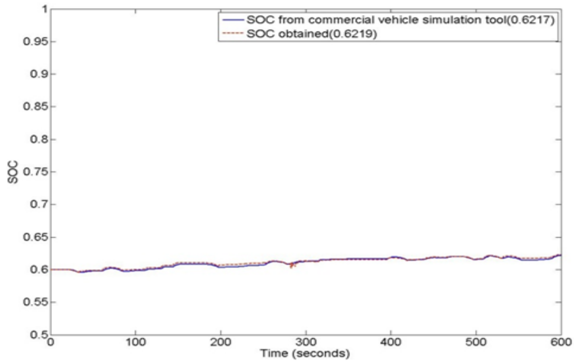

Fig. 11: SOC comparison from experiment vs. Simulation

4. Conclusions

Mathematical modelling and Simulink based simulation of a lead acid battery was presented. State of charge, terminal voltage, temperature and life were outputs from the developed simulation model. State of charge and terminal voltage from simulations were validated with experimental data and commercial vehicle simulation tool GT suite. These results obtained from the simulation model were in agreement with the experimental results.

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