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Mechanical–electrochemical modeling of Li-ion battery designed for an electric scooter

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Abstract

A macroscopic electrochemical–mechanical model was developed to predict the various power demands of an electric scooter and other outputs, such as the Li-ion battery pack current and voltage requirements for a randomly generated drive cycle using the Matlab-based Simulink software. The simulation results obtained were compared with the actual field test results of a commercial lead-acid battery pack used in a specific electric scooter. The simulation results appeared to give a realistic idea of the dynamic performance of a conceptual Li-ion battery pack in a typical drive pattern. These results, though, need to be validated in an actual field test.

Keywords: Lithium-ion battery; Thermal management; Phase change materials; Electric scooter; Thermal modeling/simulation; Air-cooling

1. Introduction

Prior modeling efforts in the Li-ion battery industry have created a shift in focus towards developing a thermal or electrochemical model, or a combination of both in predicting the thermal and electrochemical response of the Li-ion battery [1–4]. Mechanical models have also been developed to calculate the power demands of the battery in a specific drive cycle [5,6]. No specific works have been reported to study the thermal and electrochemical performance of the Li-ion battery in a scooter application taking into consideration the drive cycle, mechanical parameters of the vehicle and driving conditions.

This modeling effort will help to design and develop Li-ion batteries that employ a phase change material (PCM) thermal management system for an electric scooter. Al-Hallaj et al. [7] simulated the thermal performance of a Li-ion battery for an electric car with a passive thermal management system using phase change material to demonstrate its feasibility. In an electric scooter application where space constraint limits the use of active thermal management system, a passive PCM system proves a feasible choice. Khateeb et al. [8] described a detailed procedure of designing Li-ion batteries for an electric scooter, and presented simulation results showing the feasibility of a novel passive thermal management system for Li-ion batteries using phase change material (solid–liquid). Detailed experimental results were presented showing the thermal response of the Li-ion battery in the presence of the PCM thermal management system. Experimental results were also modeled using a simplified lumped thermal model [9]. It was important to model the dynamic electrochemical and thermal characteristics of the Li-ion battery during actual field tests as a function of the drive cycle, mechanical parameters of the vehicle and other parameters. This work presents the development of an electrochemical–mechanical model to evaluate the dynamic current, voltage, state of charge (SOC), response of the Li-ion battery as a function of a specific drive cycle and mechanical parameters of the electric scooter.

2. Model development

This modeling work allows for simulation of the performance of the Li-ion battery in the actual riding conditions of the *Zappy* electric scooter. The simulation was performed using Simulink (Matlab Version 12.1). The mechanical model calculates the

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Nomenclature

a	acceleration of electric scooter ($\mathrm{m\,s^{-2}}$)
C_a	dimensionless aerodynamic drag coefficient
C_t	dimensionless rolling resistance of tire
d	density of air ($\mathrm{kg\,m^{-3}}$)
g	acceleration of gravity ($\mathrm{m\,s^{-2}}$)
I_p	combined current of number of cells or string of series cells connected in parallel (A)
m_r	mass of rider (kg)
m_s	mass of electric scooter (kg)
n_p	number of cells or string of series cells in parallel
n_s	number of cells or string of series cells in series
P_{acc}	power demand for acceleration of electric scooter (W)
P_{aero}	power demand to overcome aerodynamic drag (W)
P_{aux}	power demanded by auxiliary systems—head lights, signal lights, horn, etc. (W)
P_{grade}	power demand on an incline (W)
P_{par}	parasitic power demanded by battery system (W)
P_{total}	total power requirement of electric motor (W)
$P_{traction}$	power demand for traction of vehicle (W)
P_{tyre}	power consumed for motion of tires (W)
R	overall resistance of Li-ion battery (Ω)
v	velocity (speed) of electric scooter ($\mathrm{m\,s^{-1}}$)
V	voltage demand of Li-ion battery (V)
V_o	open circuit voltage of Li-ion battery (V)
V_s	combined voltage of number of cells in series (V)
W_{el}	electric work (W)

Greek letters

η_m	efficiency of electric motor and controller system (75–80%)
θ	angle of inclination of road

power requirements of the electric scooter as a function of the rider weight, acceleration, road inclination, etc., whereas the electrochemical model outputs the current and the voltage profiles from the Li-ion battery based on the power demand from the electric motor. The voltage profile is generated in the simulation via an integrated empirical plot of voltage versus state of charge.

Thus, at each time step in the simulation, the capacity of the battery available is calculated based on the current consumption. As a next step, the model calculates the SOC and the calculated value is compared to the open circuit voltage versus SOC plot. Then, the computed battery OCV is used to estimate the battery voltage during discharge. The battery is at a complete charged state when SOC is 100% and at a complete discharged state when SOC is 0%.

Thus, the electrochemical and mechanical model is integrated into the Simulink and simulation is conducted under various operating conditions. The input to the model is the speed versus time data, and this data is randomly generated.

The important features of this electrochemical–mechanical model are as follows:

1. The total power requirement of the electric motor, the power output from the battery and the state of charge of the battery can be determined as a function of the speed of the scooter, acceleration, road inclination (grade) and rider weight.
2. The model can simulate any drive cycle required and verify if the Li-ion battery can meet the power requirements. If not, the number of cells needed to be connected in series or parallel to compensate the power deficit can be determined.
3. Safety circuits have become an integral part of Li-ion batteries for high wattage requirements of any application—especially automotive requirements. The safety circuit feature can also be implemented in this model where the current drawn from the battery will be limited after a threshold limit is reached.

2.1. Assumptions

1. The empirical data of open circuit voltage versus SOC used in the Simulink to predict the voltage profiles was obtained from *C*/1 rate (1-h discharge rate) constant current discharge test, though the battery could discharge at varying rates in the actual drive cycle.
2. The resistance versus DOD data is obtained from Sony 18650 (1.8 Ah) Li-ion cell at *C*/1 rate and the open circuit voltage (OCV) data is obtained from Sony 18650 (1.4 Ah) at *C*/1 rate, whereas Moli energy 18650 (2.2 Ah) Li-ion cells are used in the experimental work.

2.2. Traction power demand

The power demand for traction of the vehicle can be expressed as follows [5,6]:

$$P_{traction} = P_{grade} + P_{acc} + P_{tyre} + P_{aero} \tag{1}$$

$$P_{grade} = mgv\sin\theta \tag{2}$$

$$P_{acc} = mav \tag{3}$$

$$P_{tyre} = mgvC_t \tag{4}$$

$$P_{aero} = 0.5dC_aAv^3 \tag{5}$$

$$P_{traction} = mgv\sin\theta + mav + mgvC_t + 0.5dC_aAv^3 \tag{6}$$

where $m = m_r + m_s$.

2.3. Power demand of the electric motor

The total power requirement of the electric motor is given by:

$$P_{total} = \frac{P_{traction}}{\eta_m} + P_{aux} + P_{par} \tag{7}$$

The Li-ion battery is designed for this electric scooter using a passive thermal management system, thus eliminating any form of active cooling components such as blowers or fans. As a result, $P_{\mathrm{par}} = 0$. Also, there are no auxiliary systems, hence $P_{\mathrm{aux}} = 0$.

2.4. Power supplied by the Li-Ion battery

The voltage of the Li-ion battery is calculated using the following simplified equation [5,10]:

$$V = V_{\mathrm{o}} + IR \tag{8}$$

The power supplied by the Li-ion battery, $P_{\mathrm{batt}} = V_{\mathrm{s}} I_{\mathrm{p}}$. (9)

where

$$V_{\mathrm{s}} = n_{\mathrm{s}} V \tag{10}$$

$$I_{\mathrm{p}} = n_{\mathrm{p}} I \tag{11}$$

The discharge as a function of depth of discharge (DOD) was obtained for Sony (1.8 Ah) 18650 Li-ion cell from literature [11]. The open circuit voltage data was obtained for Sony (1.4 Ah) 18650 Li-ion cell from experiments conducted by other members in our research group. Both of these empirical data correspond to the $C/1$ rate discharge. These empirical plots, as shown in Figs. 1 and 2, are integrated into the Simulink model and the discharge voltage of the Li-ion battery can be generated as a function of depth of discharge.

The mechanical and electrochemical model is implemented in the Simulink as shown in Fig. 3. The first part of the model block diagram represents the mechanical model, which calculates the total power demanded by the electric motor from acceleration, on incline, cruising and aerodynamic power demands. The speed, rider and vehicle mass, road grade and other scooter parameters are input in this model.

The electrochemical model calculates the voltage and current output of the Li-ion battery. The input to this model consists of the empirical results of the open circuit voltage and resistance as a function of depth of discharge. The sequence of simulation performed in the Simulink is as follows:

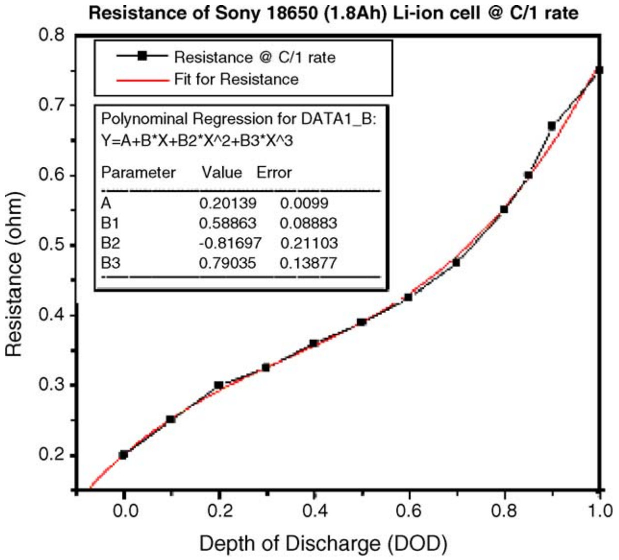

Fig. 1. Discharge resistance vs. depth of discharge (DOD) for Sony (1.8 Ah) 18650 Li-ion cell [11].

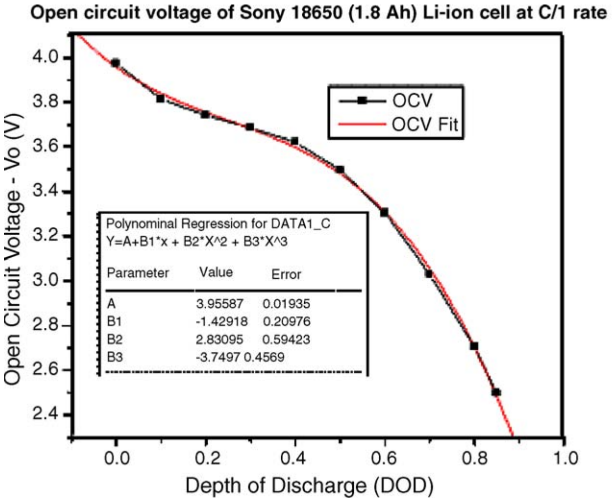

Fig. 2. Open circuit voltage (OCV) vs. depth of discharge (DOD) of Sony (1.4 Ah) 18650 Li-ion cell.

- Mechanical model
  1. The speed data from a driving cycle is input into the model along with other parameters specific to the electric scooter, rider mass and inclination of road.
  2. The total power demanded by the electric motor is calculated as a summation of different power terms according to Eq. (7).
- Electrochemical model
  1. Based on the power demand from the electric motor, the current requirement of the Li-ion battery to meet the demand is calculated according to Eq. (9). The actual amount of current that the Li-ion battery can supply is also calculated in the next step by implementing a safety current limiter in the model to simulate the function of a safety circuit.
  2. The electrical capacity consumed of the Li-ion battery is calculated by time integration of the current for every simulated time step.
  3. The depth of discharge (DOD) of the Li-ion battery is calculated by dividing electrical capacity consumed by the actual initial capacity of the battery.
  4. Based on this DOD at every time step, the resistance and open circuit voltage of the battery is calculated from the empirical results.
  5. The voltage of the Li-ion battery on load is then calculated according to Eq. (8).
  6. The above steps are executed in the loop for every simulation time step, which generates the instantaneous power, current and voltage of the electric motor and Li-ion battery.

3. Simulation results and discussion

The drive cycle shown in Fig. 4 was randomly generated and used in the dynamic simulation of the Li-ion battery module in the *Zappy* electric scooter. The various inputs to the simulation

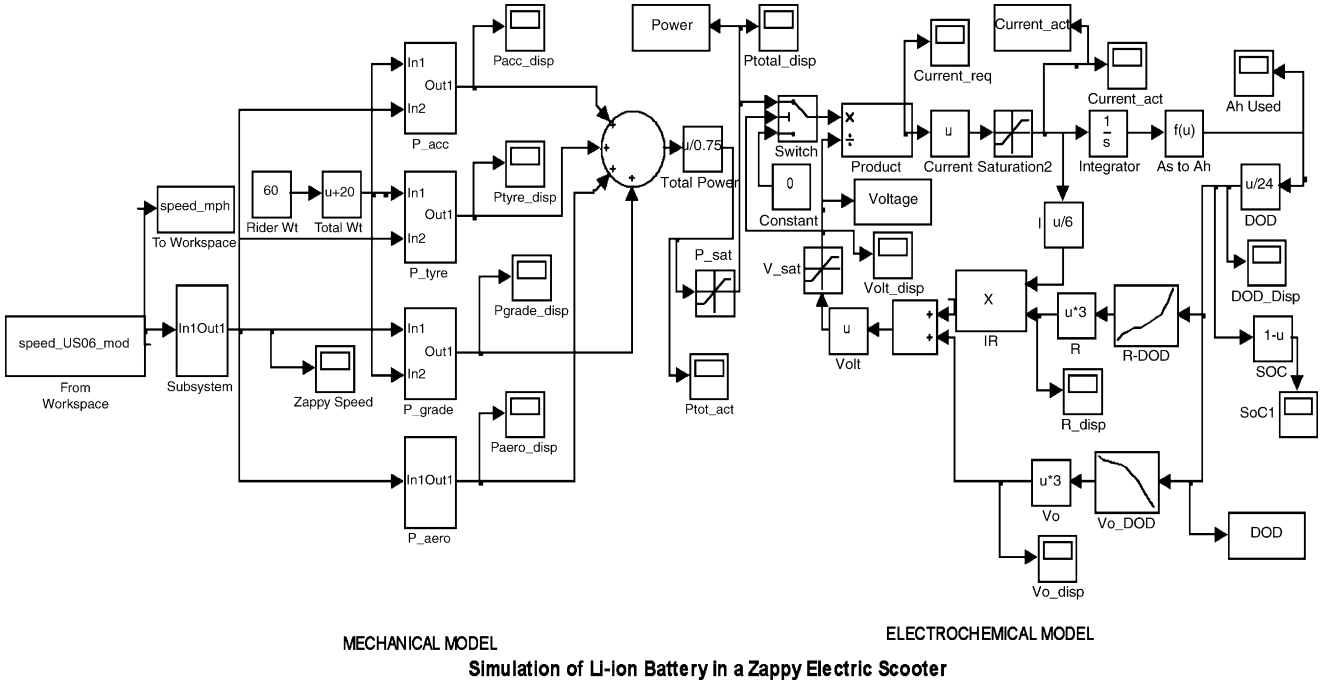

Fig. 3. Simulink block diagram of mechanical–electrochemical model of Li-ion battery in Zappy electric scooter.

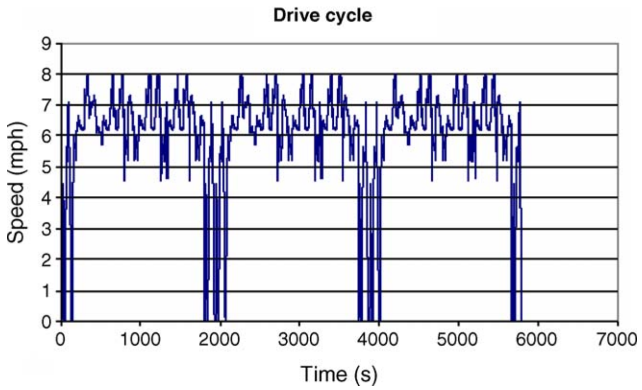

Fig. 4. Drive cycle simulated in Simulink mechanical–electrochemical model.

according to Eqs. (2–5) are summarized in Table 1. The drive cycle data, along with these input parameters are fed into the Simulink model and the simulation was performed for a time period of 4800 s. The results from the simulation yield the following important information:

1. The power requirement or demand from the electric motor as the scooter traces through the drive cycle.
2. Based on the power requirement, the discharge current output of the battery can be determined and also whether the battery will be able to sustain the current requirement throughout the drive cycle period.
3. The discharge voltage of the battery and the time duration for the battery to reach the cut-off voltage
4. The depth of discharge (DOD) of the Li-ion battery.

Table 1
List of values of parameters used in simulation

Parameters	Values
Weight of scooter, m_s (kg)	20
Weight of rider, m_r (kg)	60
Density of air, d (kg m^{-3})	1.293
Frontal cross-section area of the electric scooter, A_f (m^2)	0.5
Acceleration of gravity, g (m s^{-2})	9.81
Dimensionless rolling resistance of tire, C_t	0.008
Dimensionless aerodynamic drag coefficient, C_a	1.2

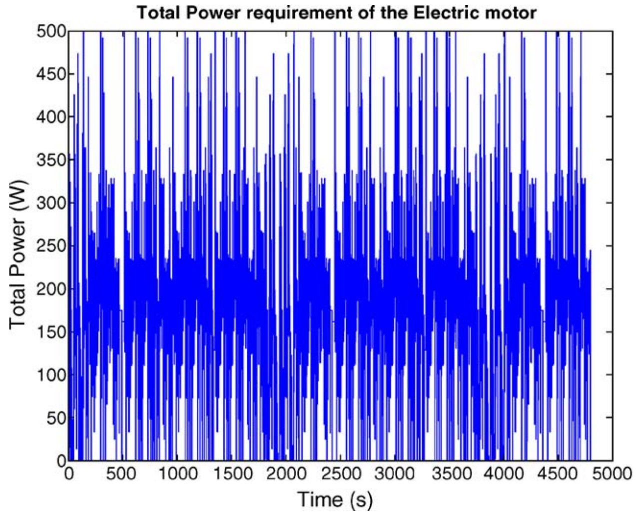

Fig. 5. Simulated total power requirement of electric motor in Zappy electric scooter.

The total power demand from the electric motor is shown in Fig. 5. The electric motor is rated at 0.5 hp (373 W) power output, though the motor can provide short bursts of peak power

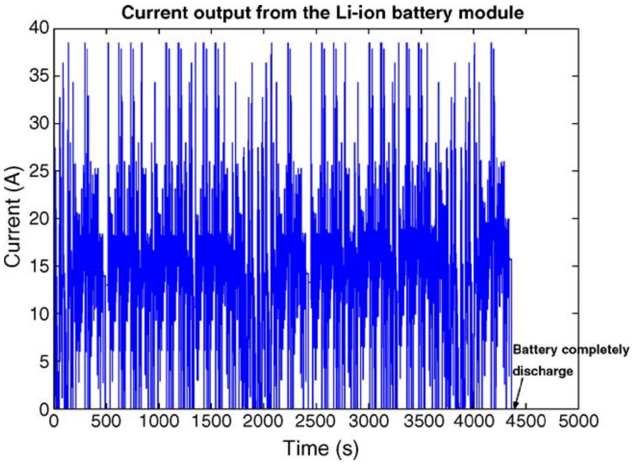

Fig. 6. Simulated Li-ion battery current output in Zappy electric scooter.

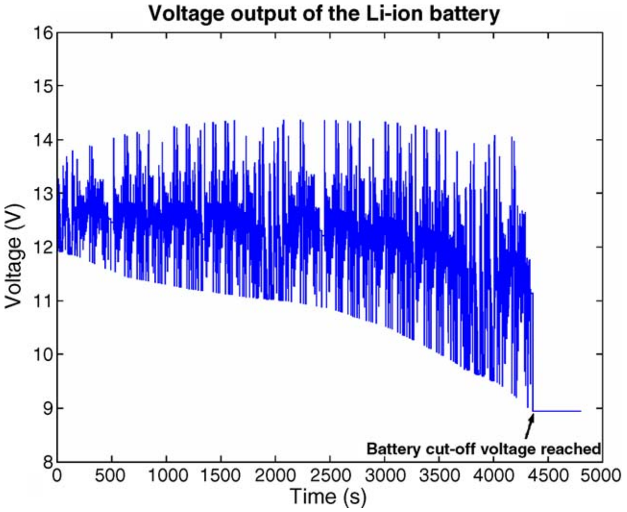

Fig. 8. Simulated Li-ion battery voltage output in Zappy electric scooter.

exceeding the power rating. The average power requirement of the electric motor is 175–225 W.

In response to the above power demand from the electric motor for traction of the electric scooter, the discharge current output of the Li-ion battery is shown in Fig. 6. The average current throughout the entire drive cycle period is about 15–18 A. The average current output of the lead-acid battery was about 18–24 A on real time field-testing of the electric scooter with a rider weight of 65 kg.

The actual field test results of the electric scooter using the lead-acid battery is shown in Fig. 7. The current output of the lead-acid battery during this field test suggests that the battery was discharged for more than a 1-h discharge rate. Ideally, the battery should be discharged within 2770 and 3600 s as per the rated capacity of 18 Ah but during the field test, the 18 Ah, 12 V lead-acid battery was able to discharge for 1950 s before the electric vehicle halted. Although, the commercial lead-acid battery was rated at 18 Ah, actual laboratory tests at 5 h and 1-h discharge rate delivered less than the rated capacity.

In the case of the simulation, the Li-ion battery with a capacity of 24 Ah, 12.6 V was able to sustain for close to 4400 s before the battery is not able to provide further current. The average current from the Li-ion battery in the simulation was about 15–18 A, which is about 75% of a 1-h discharge rate that should discharge the battery in 4800 s as per the rate capacity. One of the reasons could be that the resistance values used in the simulation corresponded to a 1-h discharge rate and the resistance of the battery should be low at 75% of the 1-h discharge rate.

The voltage response of the Li-ion battery is shown in Fig. 8. The average voltage of the Li-ion battery in the entire drive cycle is found to be 12.5 V and the nominal voltage is 11.1 V, though there exists some peak voltage reaching a maximum of 14 V. It is also important that the Li-ion battery does not over-

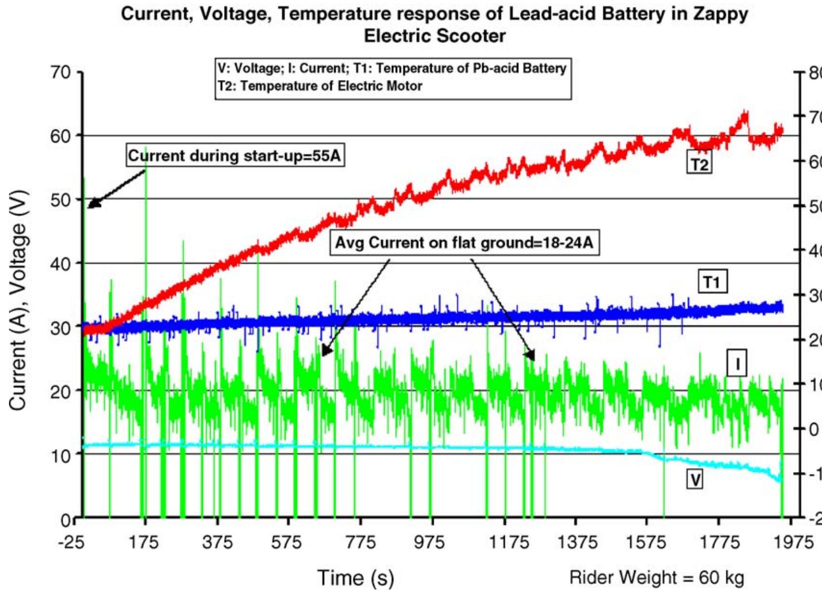

Fig. 7. Preliminary actual results of Zappy electric scooter with a commercial lead-acid battery [8].

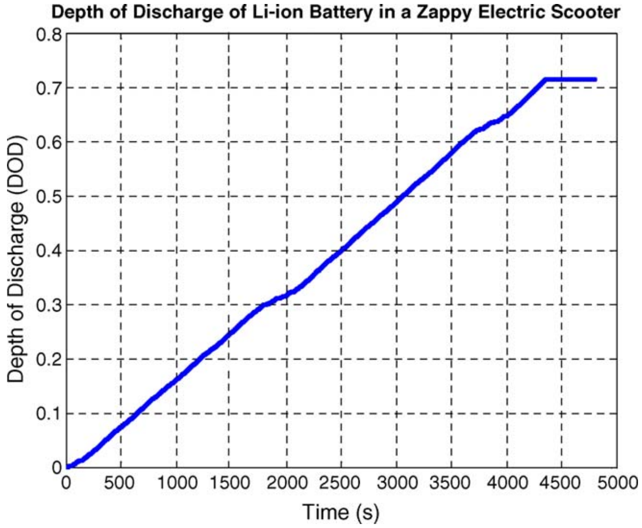

Fig. 9. Simulated depth of discharge (DOD) of Li-ion battery in Zappy electric scooter.

charge to higher voltage. The battery is found to reach the cut-off voltage of 9 V at 4400 s and the battery is simulated to shut down the power. The depth of discharge of the Li-ion battery reaches 72% at the cut-off voltage of the battery, as shown in Fig. 9.

4. Conclusions

The work presented in this paper described the development of a mechanical–electrochemical model of Li-ion battery for an electric scooter application. The Li-ion battery powering a *Zappy* electric scooter was modeled and its electrochemical performance simulated during a randomly generated drive cycle, by means of a specially developed electrochemical–mechanical model. The simulation results closely predict the power demands of the electric motor, instantaneous Li-ion battery pack voltage and current outputs.

The average current output of the Li-ion battery in the drive cycle was about 15–18 A, compared to 18–24 A measured under actual field test conditions with the lead-acid battery powering the scooter. The lower current demand on the Li-ion battery may be attributed to the higher average voltage output of the Li-ion cells, as well as the higher discharge capacity compared to the lead-acid battery. The discharge capacity of the Li-ion battery was 24 Ah, compared to 18 Ah for the lead-acid battery. The average voltage output of the Li-ion battery was around 12.5 V (with the actual nominal voltage of the Li-ion battery being 14.4 V). Once the output voltage would hit the set value of 9 V, the simulation cuts off the discharge and the vehicle would stop.

Overall, the mechanical–electrochemical model appears to give a realistic prediction of dynamic performance, which qualitatively agrees well with expectations. These simulation results have to be validated by actual field tests before further refinements to the model are justified.

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References

[1] M. Doyle, T.F. Fuller, J. Newman, Modeling of galvanostatic charge and discharge of lithium/polymer/insertion cell, J. Electrochem. Soc. 140 (June (6)) (1993) 1526–1533.

[2] C.R. Pals, J. Newman, Thermal modeling of the lithium/polymer, J. Electrochem. Soc. 142 (August (10)) (1997) 3274–3281.

[3] L. Rao, J. Newman, Heat generation and general energy balance for insertion battery systems, J. Electrochem. Soc. 144 (August (8)) (1997) 2697–2704.

[4] S. Al-Hallaj, H. Maleki, J.S. Hong, J.R. Selman, Thermal modeling and design considerations of lithium-ion batteries, J. Power Sources 83 (October (1–2)) (1999) 1–8.

[5] A.K. Shukla, A.S. Arico, V. Antonucci, An appraisal of electric automobile power sources, Renewable Sustainable Energy Rev. 5 (2001) 137–155.

[6] B. Lin, Conceptual design and modeling of a fuel cell scooter for urban Asia, J. Power Sources 86 (March (1–2)) (2000) 202–213.

[7] S. Al Hallaj, J.R. Selman, J. Electrochem. Soc. 147 (9) (2000) 3231–3236.

[8] S.A. Khateeb, M.M. Farid, J.R. Selman, S. Al-Hallaj, Design and simulation of a lithium-ion battery with a phase change material thermal management system for an electric scooter, J. Power Sources 128 (April (2)) (2004) 292–307.

[9] S.A. Khateeb, S. Amiruddin, M. Farid, J.R. Selman, S. Al-Hallaj, Thermal management of Li-ion battery with phase change material for electric scooters: experimental validation, J. Power Sources 142 (2005) 345–353.

[10] P. Nelson, D. Dees, K. Amine, G.L. Henriksen, Modeling thermal management of lithium-ion PNGV batteries, J. Power Sources 110 (August (2)) (2002) 349–356.

[11] K. Onda, H. Kameyama, T. Hanamoto, K. Ito, Experimental study on heat generation behavior of small lithium-ion secondary batteries, J. Electrochem. Soc. 150 (3) (2003) A285–A291.