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Modeling Battery Management System Using The Lithium-Ion Battery

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***Abstract*— Battery-powered electronics devices have become well-verse in the current society. The rapid growth of the use of portable devices such as portable computers, personal data assistants, cellular phones and Hybrid Electrical Vehicles (HEVs) creates a strong claim for fast deployment of the battery technologies at an extraordinary rate. The design of a battery-power-driven device requires many battery-management features, including charge control, battery-capacity monitoring, remaining run-time information and charge-cycle counting. Compare to other batteries, lithium battery has the highest power density, energy density and the longest cycle life. The main objective is to develop a battery management system model to ensure that optimum use is made of the energy inside the battery powering the portable device and that the risk of damage to the battery is prevented. Modeling a battery management system by studying the charging and discharging characteristic curve of the lithium-ion battery is being proposed in this research project.**

Keywords: Charging; Discharging; State of Charge; Lithium-ion Battery; Non-Linear Battery Model

I. INTRODUCTION

Batteries are the most common electrical energy storage devices in electrical vehicles. The performance of a battery when it is connected to a load or a source is based on the chemical reactions inside the battery. The chemical degrade with time and usage that reflect the gradual reduction in the energy storage capacity of the battery. The battery depreciation process needs to be reduced by conditioning the battery in a suitable manner by controlling it's charging and discharging profile, even various load conditions. In general, battery life time will be diminished when the battery is operated under a wide range of thermal conditions. Batteries are safe, despite reports of explosion of failure, when used with a power conditioning system that incorporates safety features and automatic shutdown. Basically there are two aspects taken into consideration to enhance battery performance. Firstly is the capability of the battery itself, which it depends on the material of the battery been constructed and the making process. Secondly is the Battery Management System (BMS) [1]

Lithium-ion battery is a family of the rechargeable battery type. It is one of the most common types of rechargeable batteries used for portable electronic devices and electric vehicle. Lithium battery is chosen as one of the best energy densities, higher power density, and has long cycling life compare to Lead-Acid battery and Nickel Metal Hydride battery. Lithium battery also has no memory effect and low self-discharges when it is not in use. Due to these characteristics, lithium-ion battery has come into people's attention more frequently. Table 1 are results that been obtain [2] to compare the parameters and the characteristics of lithium-ion battery to other 2 types of batteries. Thus, the parameters of lithium-ion battery are greater compare to Lead-Acid battery and Nickel Metal Hydride battery.

TABLE I. COMPARISON PARAMETERS OF THE DIFFERENT TYPE OF BATTERY

Category of battery	Energy density (Wh/kg)	Power density (W/kg)	Cycle life (time)	Cost ($)
Lead-acid	30~50	200~400`	400~600	120~150
NiMH	50~70	150~300	>800	150~200
Lithium	120~140	250~450	1200	150~180

The construction of lithium-ion battery includes a negative electrode, a positive electrode, separator between the electrodes, and electrolyte for submerging the electrodes. The negative electrodes is made of active materials including at least one lowly graphitizes carbon material and least one highly graphitized carbon material. The positive electrode made of active materials including lithium ion, transition metal ion and polyanion [3]

Battery Management System is defined as a control or management unit plurality of rechargeable batteries. An ideal BMS will be energy efficient, drawing as little power as possible, effective at realizing the full capacity of the batteries through effective balancing and ensure that the batteries are not being damaged by over charging, discharging or excessive current load or discharge.

An intelligent battery management system is needed because the battery chargers presently in use are shorten the life of entire sets of batteries. Proper charging and discharging of a battery can significantly lengthen its life and also produce more efficient use of the battery.

The increased interest in electric vehicles and electronic devices, Battery Management System has become one of the chief components. Battery monitoring is vital for the electric vehicles and electronic devices, because the safety, operation and the life span of the battery depends on the battery management system. Battery Management Systems (BMS) handle all monitoring, control and balancing and safety circuitry of the battery packs and control systems. Battery Management Systems effectively monitors the cell voltage, balances the voltage between the cells to maintain a constant pack voltage, and manages its charging and discharging. Besides that, the other important feature of Battery Management System is to protect the system from over-voltage and over-current conditions for packs of cells in series. It also monitor the system's temperature, handles power saving, and interact with external controllers to provide system feedbacks [4].

II. Battery Modeling

Batteries are the most common electrical energy storage devices in electrical vehicles. The performance of a battery when it is connected to a load or a source is based on the chemical reactions inside the battery. The chemical degrade with time and usage that reflect the gradual reduction in the energy storage capacity of the battery. The battery depreciation process needs to be reduced by conditioning the battery in a suitable manner by controlling it's charging and discharging profile, even various load conditions.

The research is to study on the principal characteristic of the lithium-ion batteries and modeling a cascade battery management system. All the principal characteristic of the lithium battery need to be identified and the criteria to differentiate the batteries should be known. There are basically three types of battery models, namely, experimental, electrochemical and electric circuit-based. Experimental and electrochemical models are not well suited to represent cell dynamics for the purpose of state-of-charge (SOC) estimations of battery packs. However, electric circuit-based models can be useful to represent electrical characteristics of batteries. The simplest electric model consists of an ideal voltage source in series with an internal resistance [5]. This model, however, does not take into account the battery SOC. Another model is based on an open circuit voltage in series with resistance and parallel RC circuits with the so-called Warburg impedance [6]. The identification of all the parameters of this model is based on a rather complicated technique called impedance spectroscopy [7]. Shepherd developed an equation to describe the electrochemical behaviour of a battery directly in terms of terminal voltage, open circuit voltage, internal resistance, discharge current and state-of-charge [8], and this model is applied for discharge as well as for charge. The Shepherd model is interesting but causes an algebraic loop problem in the closed-loop simulation of modular models [9]. Battery models with only SOC as a state variable are discussed in [10] [11]. These models are very similar to Shepherd's but don't produce an algebraic loop. In this paper, a model using only SOC as a state variable is chosen in order to accurately reproduce the manufacturer's curves for the four major types of battery chemistries. These four types are: Lead-Acid, Lithium-Ion (Li-Ion), Nickel-Cadmium (NiCd) and Nickel-Metal-Hydride (NiMH). In this paper the charge and discharge curve are obtained by simulation or the different type of batteries with the manufacturer's datasheet.

In order to obtain a physical charging and discharging curve, a system need to be created using the charging and discharging equation. The objective of the project is obtain when the right equation being determined for the lithium-ion battery, because the model of charging and discharging will change base on the type of battery used. Once all the calculation procedures have been identified, it needs to be translated into simulation blocks using computation software of MATLAB to be converged.

The proposed dynamic lithium-ion model also validated with another author. Figure 1 shows the results of the battery output voltage with different cycle number for 25^0C and figure 2 shows the results for the 50^0C obtained by the proposed model for discharge condition, 0.9A and 1.8Ah lithium ion battery. Where the figure 3 and figure 4 shows the results obtained by Ramadass[12] for the same condition. From the figure 1 and figure 2, can see that the proposed model and results obtained by Ramadass[12] are quite similar and also can see that, as the capacity fading significantly increases with increment of temperature and cycle number. The summary of the results is shown in the table III, for the different cycle number.

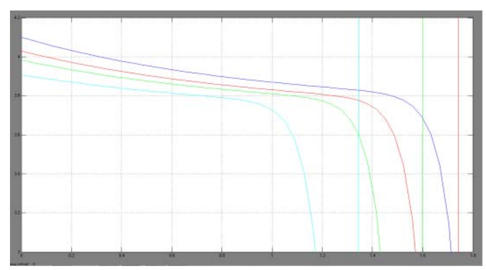


Fig. 1. Results obtained by proposal model (25°C)

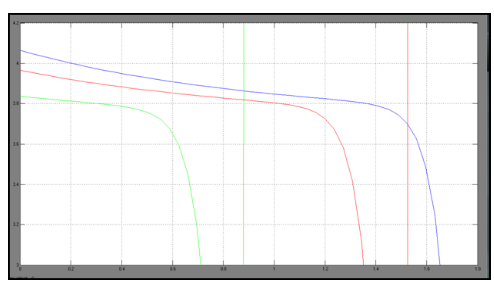


Fig. 2. Results obtained by proposal model.(50°C)

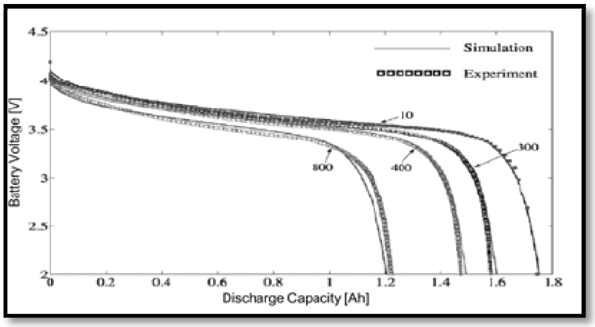


Fig. 3 Results obtained by Ramadass

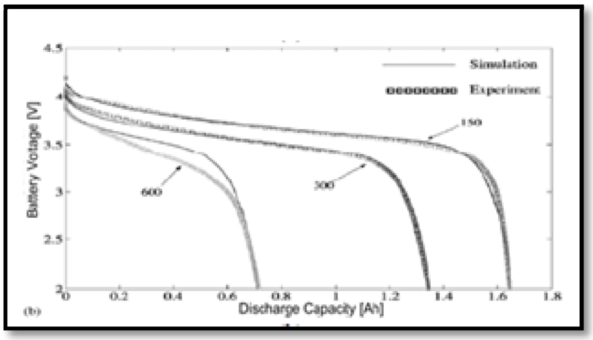


Fig 4 Results obtained by Ramadass.

TABLE II. SUMMARY OF PROPOSED MODEL AND RAMADASS RESULTS FOR 25^0C

Cycle Number	Ramadass (Remaining capacity Ah)	Proposed model (Remaining capacity Ah)
10	1.2	1.2
100	1.5	1.5
400	1.6	1.6
800	1.78	1.78

The battery usage time is reduce when the cycle number and temperature is increased. It found that, the operating temperature for the lithium ion battery is 25^0C. Table III shows the summary results for the different cycle.

TABLE III. SUMMARY OF PROPOSED MODEL AND RAMADASS RESULTS FOR 50°C.

Cycle Number	Ramadass (Remaining capacity Ah)	Proposed model (Remaining capacity Ah)
150	1.63	1.63
300	1.28	1.28
600	0.7	0.7

III. METHODOLOGY

A. Battery Charging

For the charging process, it is always assumed that the battery will be charged to reach its 100% capacity before its usage. During charging period, commonly the battery will not be connected to any load. It will be only connected directly to the charging adapter. Thus, the charging period will not produce any losses in voltage due to temperature, capacity fade or from internal resistance. However, every battery has its own life time. The chemical composite of the battery decides the internal losses of the battery. The battery's life span depends on how frequently the battery being charged and discharged. The more times the battery being charged and discharge the shorter the life span of the battery. This is because research shows that, each time the battery being charged, the life span of the battery will reduce by one cycle. Besides that, if the battery being charged while the load is being connected, the battery will not reach its maximum capability of charges (less than 100% of charges) , due to losses occurs to the presents of resistance.

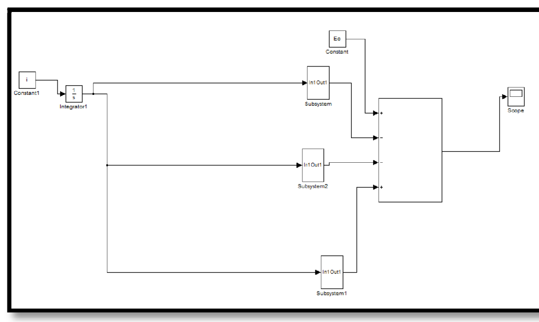


Fig. 5. Lithium-Ion Charging Model

Following are the equation for the Subsystem 1, 2 and 3 in the charging model:

$$Subsystem \ = k\left(\frac{Q}{(it+0.1)Q}\right) i \qquad (1)$$

$$Subsystem\ 1 = k\left(\frac{Q}{Q-it}\right) it \qquad (2)$$

$$Subsytem\ 2 = A * \exp(-B * it) \qquad (3)$$

B. Battery Discharge

Important parameters need to be identified before starting modeling the battery discharge curve.

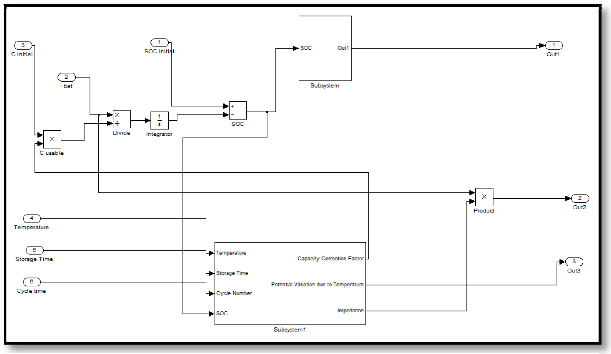


Fig 6 : Lithium-Ion Discharging Model

Battery open circuit voltage can be calculated due to the battery open circuit voltage drop result the battery equivalent internal impedance and the temperature correction of the battery potential. The battery output voltage expressed as:

$$V_{bat} = V_{OC} - i_{bat} \times Z_{eq} + \Delta E(T) \quad (4)$$

1) The battery open circuit voltage

The difference of electrical potential between two terminals of a battery when there is no external load connected is known as battery open circuit voltage. The value of open circuit voltage can be calculated as below:

$$\mathrm{V_{OC}(SOC)} = -1.301 \times \exp(-35 \times \mathrm{SOC}) + 3.685 + 0.1256 \times \mathrm{SOC} - 0.1178 \times \mathrm{SOC}^2 + 0.321 + \mathrm{SOC}^3 \quad (5)$$

The battery SOC can be expressed as:

$$SOC = SOC_{int} - \int (i_{bat} / C_{usable}) dt \quad (6)$$

2) The effect of capacity fading

Capacity fading is known as the irreversible loss in usable capacity of a battery due to temperature, cycle number and time. The capacity correction factor can be calculated as:

$$CCF = 1 - (Calendar\ life\ losses + cycle\ life\ losses) \quad (7)$$

Then the remaining usable battery capacity defined as

$$C_{usable} = C_{initial} \times CCF \quad (8)$$

During the battery is not in use, the calendar life losses of a battery consist of storage losses. The percentage of storage losses are as per below

$$\%\ storage\ loss = 1.544 \times 10^7 \times \exp\left(\frac{40498}{8.3143 \times T}\right) t \quad (9)$$

The rate of change in negative electrode SOC is dependent on cycle number and temperature can be represented as in equation (10)

$$\frac{\mathrm{d\theta n}}{\mathrm{dN}} = \mathrm{k_1 N + k_2} \quad (10)$$

Where the coefficient k_1 accounts for capacity losses that increase rapidly during adverse conditions such as cycling at high temperature, and k_2 is a factor to account for capacity losses under usual conditions of cycling [8]. The values of k_1 and k2 can be referred to the Table 10below [13]. It is interesting to notice that k2 doesn't change much due to temperature. The variations of negative electrode SOC can be considered for simulating the cycle life losses [13].

TABLE IV. TABLE 10. VALUES OF THE COEFFICIENTS DEPENDENT CYCLING TEMPERATURE

Cycling temperature [°C]	K_1[cycle^{-2}]	K_2[cycle^{-1}]	K_3[Ω/cycle$^{1/2}$]
25	8.5×10^{-8}	2.5×10^{-4}	1.5×10^{-3}
50	1.6×10^{-6}	2.9×10^{-4}	1.7×10^{-3}

3) Variable equivalent internal impedance of battery

The battery equivalent internal impedance consists of a series of resistor composed of R_{series} and R_{cycle} and two RC network composed of $R_{transient_L}$, $C_{transient_L}$, $R_{transient\_S}$, and $C_{transient\_S}$. R_{series} is accountable for instantaneous voltage drop in battery terminal voltage [13]. Meanwhile, the other component of series resistor R_{cycle} is meant to define the increase in the battery resistance with cycling. The components of RC networks are responsible for short and long-time transient's inn battery impedance. The $R_{transient\_S}$, $C_{transient\_S}$, $R_{transient_L}$ and $C_{transient_L}$ [13] value is calculated, due to battery SOC as:

$$R_{series}(SOC) = 1.562 \times \exp(-24.37 \text{ x SOC}) + 0.07446 \quad (11)$$

$$R_{transient\_S}(SOC) = 0.3208 \text{ x} \exp(-29.14 \text{ x SOC}) + 0.04669 \quad (12)$$

$$C_{transient\_S}(SOC) = 752.9 \text{ x} \exp(-13.51 \text{ x SOC}) + 703.6 \quad (13)$$

$$R_{transient_L}(SOC) = 6.603 \text{ x} \exp(-155.2 \text{ x SOC}) + 0.04984 \quad (14)$$

$$C_{transient_L}(SOC) = -6056 \text{ x} \exp(-27.12 \text{ x SOC}) + 4475 \quad (15)$$

IV. RESULTS AND DISCUSSION

A. Charging

Figure 7 shows the battery is charged at the constant voltage of 3.7348V and current of 0.2A is being supplied to the simulation. The simulation process produces a smooth charging curve as per figure 6. The battery reaches its maximum charge voltage in its Q=10Ah. Therefore, the lithium ion battery requires a short period to reach its maximum charge 3.8V.

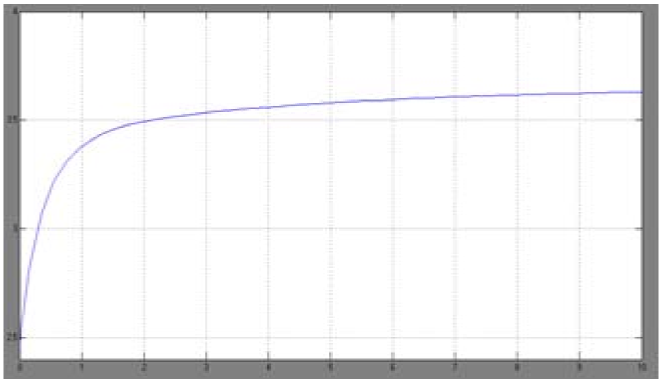


Fig.7. Charging Curve with current value of 0.2A

B. *Discharging*

Figure 8, shows the result from the discharging simulation of lithium ion battery. The battery is discharged at 4.2V and it discharging period completes at 1.7h. The model is being supplied with the current rate of 0.9A. At the time of Q=0.2Ah, the battery discharges quickly until it reaches 3.8V. Then the battery discharge at a constant value of 3.6V from Q=0.4Ah till it reaches Q=1.4Ah. Later if the battery was continuously discharged, the voltage of the battery will drop below the battery's voltage.

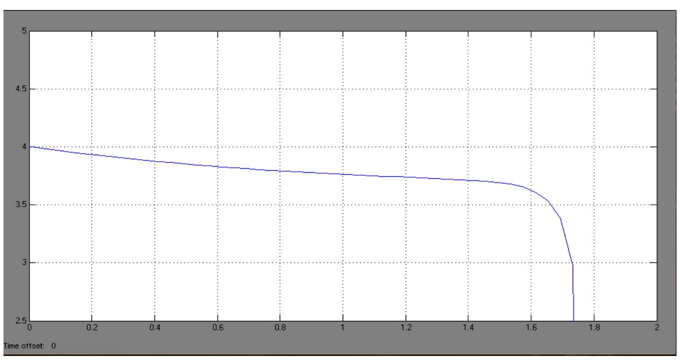


Fig. 8. Discharge Curve with SOC initial 0.89 (10 cycle time) & current value 0.9A

Figure 9, shows the overall comparison of the being discharged with different load. Table III shows the results obtain from the discharge period. It is summarized that the higher the load value (resistance), the lower its discharge capacity.

TABLE V. COMPARISON OF DICHARGING CURVES USING VARIES LOAD VALUE

LINE	CURRENT (A)	DISCHARGE CAPACITY (Ah)
1	0.80	1.60
2	0.85	1.70
3	0.95	1.90
4	1.50	0.8

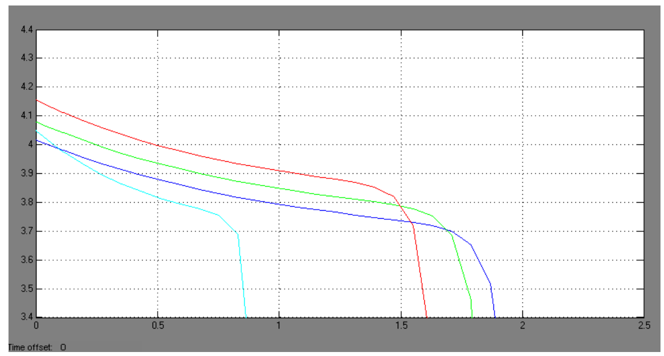
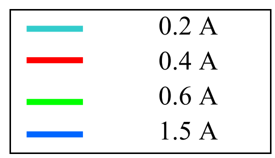


Fig. 9. Comparison of discharge curves with different loads



Line 4 in figure 9 shows the effect of over-discharge due to heavy current supply to the battery. The battery starts to discharge at 4.05V and its discharging period completes at Q=0.7Ah. This shows the battery has reached its malfunction level (damage) where it loses its storage capability.

V. CONCLUSION

In nutshell, lithium battery is chosen to be the best because it is one of the best energy density, no memory effect, long life cycle and slow loss of charge. The model chosen would be non-linear battery model whereby the model only uses state of charge (SOC) as a state variable. This mode was selected because in order to accurately reproduce the charging and discharging curve with based on assumption that been identified. This project is based on the calculation of the charging and discharging equation using the model chosen. The property if the lithium-ion battery changes when the battery being charged and discharged with the existence of load, thus it important to study the optimum load a battery could support throughout its usage period to avoid malfunctions. Besides that, the constructed battery model could be reused in the future to study other property effect such as, temperatures, storage time and state of charge effect to the battery's charging and discharging characteristic.

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NOMENCLATURE

V_{bat}	=	Battery output voltage [V]
V_{oc}	=	Battery open-circuit voltage [V]
Z_{eq}	=	Battery equivalent internal impedance [Ω]
I_{bat}	=	Battery current [A]
$\Delta E(T)$	=	Temperature correction of the potential [V]
SOC	=	State of charge
SOC_{init}	=	Initial state of charge
C_{usable}	=	Usable battery capacity [Ah]
T	=	Temperature [^{o}C-^{o}K]
t		Storage time [months]
Q_n	=	Change in state of charge of battery negative electrode
N	=	Cycle number
k_1	=	Coefficient for the change in SOC of battery negative electrode [cycle^{-2}]
k_2	=	Coefficient for the change in SOC of battery negative electrode [cycle^{-1}]
k_3	=	Coefficient for the change in R_{cycle} [Ω/cycle$^{1/2}$]
CCF	=	Capacity correction factor
C_{init}	=	Initial battery capacity [Ah]
E_{Batt}	=	Nonlinear voltage (V)
E_0	=	Constant voltage (V)
Exp(s)	=	Exponential zone dynamics (V)
K	=	Polarization constant (Ah^{-1}) or Polarization resistance (Ohms)
i*	=	Low frequency current dynamics (A)
i	=	Battery current (A)
it	=	Extracted capacity (Ah)
Q	=	Maximum battery capacity (Ah)
A	=	Exponential voltage (V)
B	=	Exponential capacity (Ah)$^{-1}$

REFERENCES

[1] Cheng, K., Divakar, B., Wu, H., Ding, K., & Ho, H. F. (2011). Battery-management system (BMS) and SOC development for electrical vehicles. *Vehicular Technology, IEEE Transactions on, 60*(1), 76-88.

[2] Siguang, L., & Chengning, Z. (2009). Study on battery management system and lithium-ion battery. *Computer and Automation Engineering, 2009. ICCAE'09. International Conference on,* 218-222.

[3] Li, X., Xu, L., Hua, J., Lin, X., Li, J., & Ouyang, M. (2009). Power management strategy for vehicular-applies hyrid fuel. *Journal of Power Sources* , 542-549.

[4] Grant Gothing, Bloomy Controls, USA. (n.d.). Functional Testing of Vehicle Battery Management Systems (BMS) using a PXI Platform .

[5] Dürr, M., Cruden, A., Gair, S., & McDonald, J. (2006). Dynamic model of a lead acid battery for use in a domestic fuel cell system. *Journal of Power Sources, 161*(2), 1400-1411.

[6] Kuhn, E., Forgez, C., Lagonotte, P., & Friedrich, G. (2006). Modelling ni-MH battery using cauer and foster structures. *Journal of Power Sources, 158*(2), 1490-1497.

[7] Mauracher, P., & Karden, E. (1997). Dynamic modelling of lead/acid batteries using impedance spectroscopy for parameter identification. *Journal of Power Sources, 67*(1-2), 69-84.

[8] Shepherd, C. M. (1965). Design of primary and secondary cells. *Journal of the Electrochemical Society, 112*, 252

[9] Plett, G. L. (2004). Extended kalman filtering for battery management systems of LiPB-based HEV battery packs: Part 3. state and parameter estimation. *Journal of Power Sources, 134*(2), 277-292.

[10] Tremblay, O.; Dessaint, L.-A.; Dekkiche, A.-I. A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehices Vehicle Power , *Propulsion Conference, 2007. VPPC 2007. IEEE Publication Year: 2007* , Page(s): 284 - 287

[11] http://www.Battery university.com

[12] Ramadass, P., Haran, B., White, R., & Popov, B. N. (2003). Mathematical modeling of the capacity fade of li-ion cells. *Journal of Power Sources, 123*(2), 230-240.

[13] Erdinc, O., Vural, B., & Uzunoglu, M. (2009). A dynamic lithium-ion battery model considering the effects of temperature and capacity fading. *Clean Electrical Power, 2009 International Conference on,* 383-386.

[14] Mumtaj Begam K, Novel 4-V Class Ultrafine Lithiated Transition Metal Power Oxides For Advanced Power Sources, PhD Thesis, 2004.

[15] Karden, E., Ploumen, S., Fricke, B., Miller, T., & Snyder, K. (2007). Energy storage devices for future hybrid electric vehicles. *Journal of Power Sources, 168*(1), 2-11.

[16] http://en.wikipedia.org/wiki/Lithium-ion_battery. (n.d.).

[17] Baer, J. T., Davis, B. C., & Blanyer, R. J. (1997). *Battery Management System,*

[18] Chen, M., & Rincon-Mora, G. A. (2006). Accurate electrical battery model capable of predicting runtime and IV performance. *Energy Conversion, IEEE Transactions on, 21*(2), 504-511.

[19] Crompton, T. R. (2000). *Battery reference book* Newnes.

[20] Spotnitz, R. (2003). Simulation of capacity fade in lithium-ion batteries. *Journal of Power Sources, 113*(1), 72-80.

[21] Xu, D., Wang, L., & Yang, J. (2010). Research on li-ion battery management system. *Electrical and Control Engineering (ICECE), 2010 International Conference on,* 4106-4109.

[22] Charles J Scuilla (2007) Research on the Commercialization of Lithium Battery, *Scuilla Paper,* 16,1-16,9